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Management of Coal Preparation Fine Wastes without Disposal Ponds

Interagency Energy/Environment R&D Program Report

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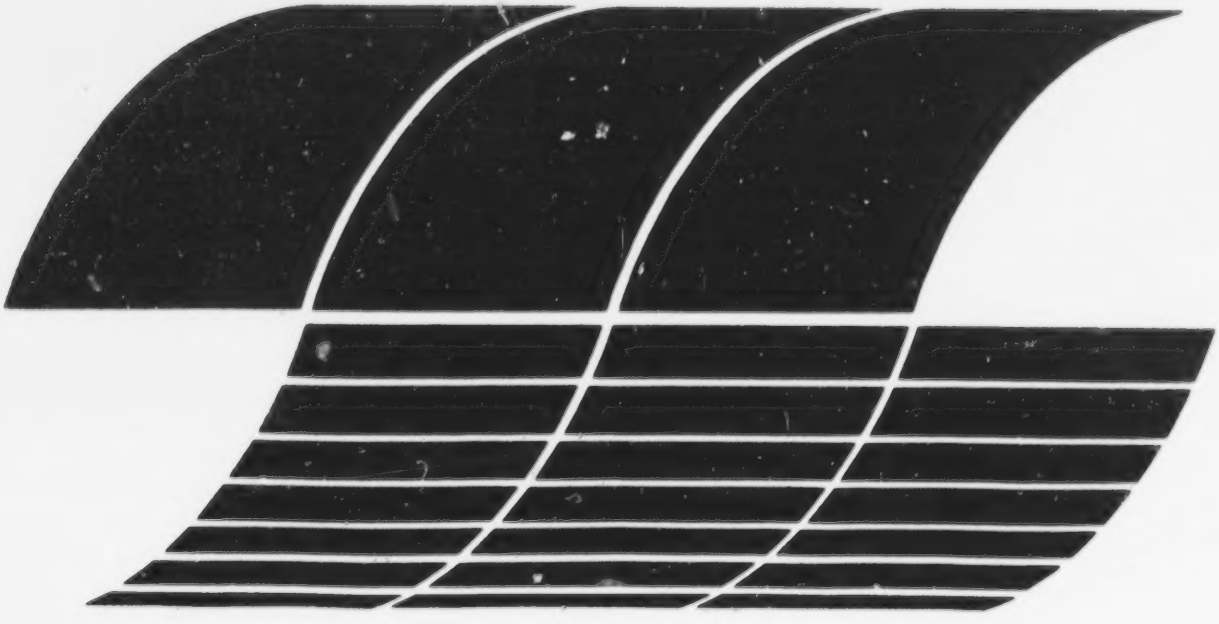

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by

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Management of Coal Preparation Fine Wastes Without Disposal Ponds

Final Report

July 1, 1977 to June 15, 1978

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ABSTRACT

In the beneficiation of coal, the common medium for upgrading the mined coal is water. The end products of coal beneficiation are generally three materials; (1) the clean coal, (2) coarsely sized waste product, and (3) a finely sized waste product. As the need for cleaner coal increases, the amount of waste products generated also increases and the importance of safe, environmentally acceptable disposal of these wastes becomes more important.

Generally, the coarse refuse (plus 28 mesh) can be disposed of safely because it is a solid with inherent engineering properties that can be utilized in engineered structures. However, the fine refuse (minus 28 mesh) generally exists as a water-based slurry devoid of significant engineering properties that can be employed in engineering disposal methods.

The objective of this study is to ascertain some physical/chemical properties of a diverse sampling of fine coal refuse and to investigate the effect of chemical stabilization. Samples of fine coal refuse were obtained from some of the major coal seams in the Eastern bituminous coal fields. Two common and one proprietary chemicals were employed in testing chemical stabilization on nine samples of fine coal refuse. This study indicated that chemical stabilization can be employed to drastically improve some physical/chemical properties of the fine refuse for better handling and disposal. The proprietary chemical, Calcilox® additive, is the most effective over the range of samples tested. Portland Type I cement is also effective but greatly influenced by waste solids concentration. The final chemical tested, lime, is inferior to the other two chemicals and generally ineffective in improving the fine waste's physical/chemical properties.

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SUMMARY

With the increasing importance of bituminous coal as a domestic energy source and/or chemical feedstock, the amount of coal produced between now and 1985 is expected to dramatically increase. In 1975, 648 million tons of coal were mined, and it is projected that by 1985, 1.2 billion tons will be needed. In 1975, approximately 374 million tons of run-of-mine coal were mechanically cleaned resulting in an estimated 15 million tons of fine coal refuse (minus 28 mesh) and nearly 95 million tons of coarse coal refuse (plus 28 mesh). This cleaning was accomplished in 388 cleaning plants which are primarily located east of the Mississippi River. Nearly 80% of the cleaning plants are in the states of West Virginia, Kentucky, Pennsylvania, and Virginia; listed in decreasing number of plants per state.

The geographic location of these plants significantly influences the economic, environmentally acceptable, and safe disposal of the refuse due to the physical/chemical properties of the refuse. The coarse refuse fraction has been studied and disposed of quite safely over the years and sound engineering can handle this waste. The fines fraction has also been studied to some extent, and it has been generally concluded that this material does not possess any definite engineering properties that can be utilized by conventional civil engineering and construction methods. The fine refuse consists of very fine particles of coal, rock, and clayish substances in a water slurry ranging in dry solids content from approximately 15% to as high as 80% solids. These fines are very difficult to dewater to higher solids concentration (>65% solid) and even then, they still exhibit fluid-like properties. Even if the fluid properties can be temporarily overcome by high initial solids ($\sim$75-85% solids) for immediate handling, the material will readily reslurry and the fluid properties will reappear. These slurries can remain physically and chemically unstable for years. Thus, topography that ranges from steeply mountainous to very hilly is not conducive to above ground disposal of fine coal refuse.

Until recently, the commonly accepted method of fines disposal was either a permanent or temporary settling pond or a large impoundment of coarse refuse containing the fluid fines. During the past 10 to 20 years, great emphasis has been placed on various dewatering devices (vacuum disc filters, centrifuges, and pressure filters) to decrease the moisture content of the fine refuse. The primary objective has been to increase its immediate handling properties for landfill-type disposal of the fines with the coarse fines. These efforts have generally overlooked the actual engineering stability of the fines and have relied heavily on the overall stability of the combined coarse and fines mixture. As it has been repeatedly shown, this small amount of fines refuse can easily upset the whole disposal area.

Since 1970, Dravo Lime Company has been engaged in research into the chemical stabilization of inorganic industrial waste slurries. As a result of this work, Dravo has developed a material, Calcilox additive, that has been successfully applied to the stabilization of flue gas desulfurization sludges in the electric utility industry. Preliminary research has indicated that Calcilox alone or in combination with other known stabilizing materials can stabilize fine coal refuse as produced by today's mechanical coal cleaning plants. Therefore, the objective of this study was to stabilize a wide sampling of fine coal refuse with three stabilizing agents - Calcilox additive, lime, and Portland Type I cement. Various laboratory tests were performed to determine if these agents can impart definitive engineering properties to these fine refuse solids.

Since each preparation plant waste disposal method might be considered unique and chemical stabilization has not been proven on a full scale basis, the scope of the study was to investigate the possibility that chemical stabilization may have universal applicability to all fine coal refuse streams. In addition, the geographic area of concern would be the states that have the most need for more viable alternatives for fines disposal; mainly, West Virginia, Pennsylvania, Virginia, Kentucky, and the mid-Western states of Ohio, Indiana, and Illinois. Thus, sample selection was from these geographic areas with selection parameters being coal seam, coal application, mining type, plant circuitry, and fines handling. Important constraints in the program were ease of plant participation, ease of sampling, and budgetary considerations. As a result of these limitations, nine plants were involved in the study; four from Pennsylvania, two from West Virginia, and one each from Virginia, Indiana and Illinois. The capacity of these plants represents nearly 10 million tons of clean coal which accounts for approximately three percent of the 1975 clean coal production. The seams mined represent some of the major steam and metallurgical seams in the Eastern bituminous coal fields. Samples included both strip and deep mines employing conventional, continuous, and longwall mining methods. The preparation circuitry ranged from simple jig plants to multi-circuit cleaning plants. Fines disposal methods included unthickened plant discharge into abandoned strip pits to vacuum filter cake disposal with the coarse refuse.

The laboratory objective was three-fold: (1) Determine some engineering properties of the untreated fines; (2) Evaluate the effective chemical stabilization of the fines with the use of three substances (lime, Portland Type I cement, and Calcilox additive); and (3) Determine the engineering properties of the stabilized samples. Properties of the untreated fines that were determined were:

1. Solids chemical analyses
2. Supernatant chemical analyses
3. Particle size analyses
4. Settling rate and settled solids concentation

5. Atterberg limits
6. Solids specific gravity
7. Proctor densities
8. Permeabilities of settled slurry and filter cake
9. Direct shear properties, settled slurry and filter cake
10. Consolidation properties
11. Vacuum filtration data
12. Unconfined compression data

Stabilization data were determined with the chemical additives at three dosage levels (5%, 10%, and 15%, on a dry solids basis), and at three solids levels (25%, 35%, and filter leaf test solids). Stabilization data were evaluated as a time rate gain of penetration resistance (tons per square foot) for a 90-day stabilization period. More accurate stabilization data were obtained by performing unconfined compressive tests on specimens stabilized for forty days. For this study, improved unconfined compressive strengths were regarded as the desired result from chemical stabilization of the untreated fines. The following is a brief description of the Summary Tables:

1. Solids Chemical Analyses - Table IV

   Constituents are typical of fine coal refuse with ash contents ranging from 24% to 59% and correspond with calorific values ranging from 11,680 to 5,294 Btu/lb., respectively. Major constituents of ash are SiO_2, Al_2O_3, and Fe_2O_3. Table IV illustrates that considerable Btu are being wasted in fine refuse.

2. Supernatant Chemical Analyses - Table V

   Major constituents are sulfate, calcium, magnesium, and sodium in the liquid portion of the fine refuse slurries. With the exception of one sample, the pH values are in the pH 7-8 range.

3. Particle Size Analyses - Table VI

   The samples exhibit a wide range of particle sizes. However, five out of the nine samples have a large weight portion below 20 microns.

4. Settling Test - Table VII

   It appears that all the samples will settle to greater than 40% solids in approximately two days. Review of the settling curves illustrates that all the samples will be positively affected by a thickener. That is the solids from a preparation plant can be increased within the retention time of most modern-day thickeners (8 to 12 hours). Also the various chemical additives will affect the settled solids concentration.

5. Vacuum Filtration Data - Tables VIII and IX

The filter leaf test summary (Table VIII) indicates that all the slurries starting at 35% solids can be filtered to 60-70% solids. Existing full scale filters confirm this solids level to be realistically achievable. However, it should be noted that there are solid losses in the filtrate which will eventually affect a full scale filter operation by lowering the percent filter cake solids and/or yield. Utilizing a pilot rotary drum filter (Table IX), higher filter cake solids were obtained. It should be realized that the starting solids were substantially higher than typical of thickener underflow feeds to vacuum filters. Continuous operation of a drum filter would yield lower solids and yields due to cloth blinding.

6. Proctor Determination - Table X

Illustrating the problem of dewatering fines is the comparison of optimum moisture content and that achieved by filtering. It should be noted that the filter cake solids are abnormally high because the starting material is settled slurry. Real situations will not achieve these high values. The Proctor determined optimum moisture content is less, in all cases, than can be achieved by conventional vacuum filtration.

7. Permeabilities - Table XI

Permeabilities of the settled solids are quite low, 10^{-5} to 10^{-6} cm/sec., and are further reduced by vacuum filtration.

8. Consolidation Data - Table XII

The low values for the compression index, C_c, imply that the fine refuse is incompressible. In addition, the recompression index, C_{cr}, is extremely low revealing that there is no rebound in the fines after the compression stress is removed or relaxed. The water content is significant after testing and may be a major contribution to the low values of compression and recompression index. Another factor may be the solid coal or waste particles in the fines.

9. Direct Shear - Table XIII

Primarily, the instability of fine refuse is due to the lack of any cohesive strength in the untreated slurries. This is shown in both the settled slurry and filter cake. In no case does the cohesive strength achieve 1 pound per square inch (psi).

10. Unconfined Compressive Strength - Table XIV

The untreated fines were allowed to stand for 40 days after being mixed at 25%, 35%, and filter cake solids consistencies. Temperature effects were evaluated by placing duplicate samples at two different temperatures; 35°F and 72°F. Only two filter cake specimens attained any measurable strength; 1105 and 1112. These strengths were very low (4 to 6 psi) and are probably attributed to compaction strength attained while placing the semi-rigid filter cake into the specimen mold.

The overall objective of this study was to determine if fine coal refuse can be chemically stabilized. The study utilized three chemical additives and these were applied to three solids concentrations; 25%, 35%, and filter cake levels. These solid levels were chosen because Dravo's experience has shown that 25% is the minimal solids level for economic viability of a chemical stabilization approach. The 25% to 35% solids level would be representative of a thickener underflow solids range, while the higher filter cake values would be typical of disc filter and centrifuge cakes.

Based on study limitations and Dravo's expertise, a 40-day stabilization period was chosen as the maximum curing time before testing. The parameter chosen for evaluating stabilization was unconfined compressive strength. Table XIV summarizes the data obtained. Briefly it illustrates:

1. Thickener underflow solids will not stabilize with the additive dosages of 5% to 15%, by dry solids weight, using either hydrated lime or Portland Type I cement.

2. The addition of Calcilox to thickener underflows will improve their unconfined compressive strength. In 1 of 9 samples, the 5% addition did not produce any strength improvement. At the 10% Calcilox level, all solids levels and all samples showed strength improvement.

3. The addition of 5% to 15% lime to filter cakes does produce some strengths.

4. The addition of 5% to 15% Portland Type I cement to filter cakes produces significant strength improvements.

5. The addition of 5% to 15% Calcilox to filter cakes produces significant strength improvements.

6. With the use of Portland Type I cement and Calcilox for stabilization, the effect of temperature is not clearly illustrated. At the 15% Calcilox dosage level to thickener underflows, increased temperature does not always affect the stabilization rate. This tends to imply that stabilization is not 100% chemical but a combination of chemical and physical effects.

Correlation between various physical/chemical parameters and stabilization results was attempted with mixed results. Manually analyzing the various parameters obtained, a ranking of the various samples was shown, Table XVII-B. Expansion of this approach via a computer statistical package was performed attempting to correlate various parameters with unconfined compressive strength. This was not successful and attributed to errors within the data.

CONCLUSIONS

Based on this sampling of fine coal refuse, the following conclusions can be made:

1. Major constituents of fine coal refuse are coal, SiO_2, and Al_2O_3.

2. There is significant BTU value in the fine coal refuse.

3. The pH of the fine coal refuse is generally within a pH 7-8 range unless it contains highly oxidized pyritic sulfur.

4. Liquid phases of fine refuse slurries do contain appreciable dissolved solid species.

5. Particle size distributions are varied and can contain appreciable quantities of fine particles less than 325 mesh.

6. Fine coal slurries can be settled to higher solids with the use of conventional thickeners.

7. Conventional dewatering devices (vacuum filters and centrifuges) will not achieve the optimum fines Proctor density. Typical field methods of compaction for fine refuse (dozer treads) will also not achieve this value.

8. Fine coal refuse settled solids and filter cakes exhibit low permeabilities in the order of 10^{-5} to 10^{-7} cm/sec.

9. Fine coal refuse settled solids and filter cakes do not possess significant cohesive strengths, $\sim$1 psi.

10. Fine coal refuse slurries may be considered incompressible and exhibit virtually no rebound after the compressive load is relaxed.

11. Calcilox additive will generally improve the unconfined compressive strength of fine coal refuse materials with greater than 25% solids concentration.

12. Overall, Calcilox additive stabilization is superior to lime and Portland Type I cement in stabilizing fine coal refuse.

13. Lime and Portland Type I cement are only effective on fine coal refuse materials of filter cake solids consistency.

14. In comparing Portland Type I cement with Calcilox on filter cake applications, Calcilox appears to gain more strength. The rate of strength gain appears to be comparable.

15. Temperature affects chemical stabilization, that is, the warmer, the faster the rate of stabilization.

16. Technically, chemical stabilization will improve the handling and disposal of fine coal refuse.

17. Statistical correlation of the data was not possible although correlations were evident.

18. Additional data points are needed to gather statistically significant information on chemical stabilization.

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DISCUSSION

Background

As previously stated in the Summary section, the United States has an energy goal of producing 1.2 billion tons of bituminous coal by 1985. This coal will probably come from an expansion of the existing Eastern bituminous coal fields and from the new Western fields. The major consumers of bituminous coal are the steel industry and the steam electric generating industry. These two consumers are primarily located east of the Mississippi River. The demand for coking coal is principally filled from the Eastern fields and the utility coal for this area is still being supplied by the Eastern market. These two industries are using two types of coal, metallurgical and steam coal, that are different in their physical/chemical properties yet they have some things in common. As environmental and economic pressures continue, beneficiation becomes more important and more complex in order to supply these "spec" coals. Generally, they both receive some degree of beneficiation even though it may only be sizing.

Three solid product streams are generated when coal is cleaned (beneficiated):

1. Clean Coal
2. Coarse Refuse (plus 28 mesh in size)
3. Fine Refuse (minus 28 mesh in size)

The handling of the clean coal does not present any unmanageable problems. However, the handling and disposal of the coarse and fine refuse can and does present problems that can be so severe as to cause loss of life, property, and production. The major refuse problem is the fluidity of the fine refuse that can cause it to flow like water. Increasing the problems with coarse and fine coal refuse handling and disposal is the use of modern-day high production mining methods such as continuous miners and longwall mining. Overall, the handling and disposal problems can be attributed to the mineralogy of the solids and their size consist. Nearly 80% of the cleaning plants are located in the states of West Virginia, Kentucky, Pennsylvania, and Virginia. The topography of the coal sections in these states is steeply hilly to mountainous and containment of a fluid mass such as fine coal refuse is not easily done in an economic, environmentally acceptable, and safe manner.

The extent of knowledge on the disposal aspects of the fines fraction is quite limited, whereas the coarse refuse has been studied and definitive engineering properties on the general nature of the material are available. Primarily, the fine refuse behaves as a thixotropic substance that is a function of its percent solids and method of handling. Because of this thixotropic behavior,

the commonly accepted method of fines disposal is either a permanent or temporary settling pond or a large impoundment of coarse refuse in which the fines have been mixed. Currently, these disposal methods may not be the most economic or environmentally acceptable.

In recent years great emphasis has been placed on various dewatering devices (vacuum disc filters, centrifuges, and pressure filters) to increase the solids content of the fines refuse. By doing so, the immediate handling properties are improved but the actual stability of the fine coal refuse is still unknown. Reportedly, fines stability can be achieved if a solids threshold level for eliminating thixotropic behavior is exceeded. For each refuse, this level is different but solids values ranging from 85% to 92% have been reported as the stable solids level. Currently, the only physical way of attaining stability is by pressure filtration and/or combination with the dry coarse refuse to achieve an overall refuse moisture content in the acceptable range. Unfortunately, this method is quite expensive and rarely achieves the desired stability. Several methods of chemical stabilization of the fines have been investigated but have been unacceptable based on technical results, economic value, or a combination of each. Overcoming the economic barriers to chemical stabilization can be achieved with commodity substances such as lime or Portland Type I cement. However, technical problems still remain with the use of these agents.

Dravo Lime Company has developed a chemical stabilizing agent, Calcilox additive, and has successfully demonstrated its effectiveness on flue gas desulfurization waste slurries. Preliminary research has indicated that Calcilox additive alone or in combination with other known stabilizing materials can stabilize fine coal refuse as produced by today's mechanical coal cleaning plants. Therefore, the objective of this study was to treat fine coal refuse samples with lime, Portland Type I cement, and Calcilox additive to determine if they would stabilize. The test parameter for quantifying stabilization was unconfined compressive strength. To measure the effects of these chemical additives, unconfined compressive tests were also run on the untreated fines. In addition, various other physical/chemical tests were performed on the untreated material to gain more insight into the engineering properties of the fine coal refuse. An in-depth study was not undertaken since the wide-ranging applicability of chemical stabilization of fine coal refuse is yet to be proven. The area to be explored was the universality of chemical stabilization to improve the handleability and disposal of fine coal refuse.

Sample Selection

The scope of the study might be considered a "shot gun" approach in that we attempted to obtain samples that represent major coal seams, various preparation circuitry, steam and metallurgical applications, strip and deep mines, geographic location, and various fine refuse disposal modes. Timing and monetary constraints in the study dictated major reliance on Dravo's experience within the coal industry for plant selection. The plant qualifications that were initially predetermined were:

1. Plant must be in the Eastern bituminous coal field and in a major coal producing area.
2. Plant must be processing a major coal seam.
3. If possible, the plant should only be processing one seam.
4. The final sample mix should contain a wide variety of preparation circuitry.
5. The final sample mix should contain various disposal modes.
6. The preparation plant should be a fixed plant of reasonable size--greater than 200-300 tons per hour (TPH) run-of-mine capacity.

Based on these initial qualifications, it was decided to obtain samples from Central Pennsylvania, Western Pennsylvania, Southern West Virginia--Virginia area, Alabama, and the Mid-western coal field.

Initial screening of the plants in these localities was aided by the 1976 Keystone Coal Industry Manual. Using the manual and our experience, an initial list of twenty plants was formulated. Letters of introduction and scope definition were sent to the major operating executives of these twenty plants requesting an initial site visit. Initial response was quite favorable with only two plants refusing to allow an initial visit. The main reason was their feeling that any participation, although actual names would not be used by Dravo in reporting the data, would lead to further Federal regulations and intervention into their particular problems. Twelve site visits were undertaken in July and August, 1977. From these twelve plants, ten were selected for plant sampling and study participation with the understanding of complete anonymity in reporting the data. In return for the plants' participation, their own results will be supplied to them at the end of the study. The plants selected were:

1. Three from Western Pennsylvania
2. One from Central Pennsylvania
3. Three from West Virginia--Virginia region
4. Two from the Midwest
5. One from the Southeast

Due to a prolonged wildcat strike that extended well beyond our sampling phase, the plant from the Southeast was not sampled. Table I, Sample Preparation Plant Summary, tabulates the actual plant data. These mine plants produce an estimated 10,400,000 tons per year (TPY) clean coal. Compared with the 1975 statistics for clean coal production of 374 million tons, this sample represents 3% of the production in 1975. During the past few years, clean coal production has not changed very much; therefore, a 3% sample estimate is probably valid for 1977-78 production figures.

Sample Collection

Samples were taken from the preparation plant discharges prior to entering ponds, impoundments, or mechanical dewatering devices. The sample was composited over a reasonable length of time (typically four hours) during normal plant operations. Table II, Sample Preparation Plant Disposal Summary, briefly describes the fine coal refuse disposal at each location. As expected, mines that have strip operations are utilizing them for fines dispsoal, especially where land area is favorable and abundant as in the Midwest. In addition, those plants with ample land area do not employ thickeners but rely on large, permanent settling ponds located in the stripped-out areas. Plants 1104, 1113, and 1114 are the plants pumping directly to abandoned strip pits.

The only way that we have of surmising whether or not the sample is representative of their normal operations is from conversations with the plant personnel while sampling and our experience in analyzing the data after the sample is taken. Based on sampling conditions or our experience, the following plant samples might be unrepresentative:

1106 - Sample is a grab sample due to sampling constraints
1111 - Sample is a grab sample due to preparation plant upsets. Solids level, 8.8%, is very low for a thickener underflow.

Laboratory Program

In conjunction with determining the effects of chemical stabilization, an alternate objective was to gather physical/chemical information on the untreated fine refuse. A goodly portion of the laboratory program was devoted to this task. Table III, Laboratory Testing Program Outline, lists the testing program that was employed. The Index Properties (excluding certain settling tests) Engineering Properties, and Filtration Tests dealt with the untreated fines as settled solids on filter cakes. The stabilization tests were of prime importance in evaluating the effects of the chemical additives: lime, Portland Type I cement, and Calcilox additive. Stabilization tests were performed to evaluate treating thickener underflows at normal underflow concentrations (25% to 35% solids, dry weight basis)

and higher solids concentrations similar to that which is produced in vacuum disc filters and centrifuges. Since we were concerned with a chemical reaction, temperature effects were also considered. A brief description of the pertinent test methods used is in the appendix.

Physical/Chemical Data

Table IV, Chemical Analyses of Solids From Fine Coal Refuse Samples, lists various parameters of the fine refuse solids. In the refuse solids, ash, fixed carbon, BTU/lb., percent solids, and pH are important. The ash, fixed carbon, and BTU/lb. are all related to the amount of coal that is in the waste. Dravo has found that well run preparation circuits will discharge waste with 40-60% ash and will possess a heat value of 5000 to 7000 BTU/lb. Four out of nine samples fell into this category: 1104, 1111, 1113 and 1114. Three of the nine samples, 1105, 1106, and 1112, contained a large amount of coal, greater than 10,000 BTU/lb. Plant 1105 personnel realize they discharge coal and make an effort to reclaim the pond settled solids. Elimination of the coal discharge can only be achieved by preparation circuit modifications. On the contrary, 1106 is operated by the same company and is a relatively new plant. Sampling and temporary plant problems may have resulted in this non-representative, high BTU sample. No explanation is readily apparent for the coal losses at 1112. In general, significant BTU/lb. can be found in the fine coal refuse and it may be worth recovering.

The pH values are within reason except for 1104 and this is explained by their mining method. They are stripping pillars from an old underground mine and the coal must be highly oxidized resulting in acid mine drainage. In fact, the prep plant's major problem is equipment corrosion. Experience indicates that plants without thickeners will produce 10 to 15 percent solids discharge whereas thickeners do concentrate the solids more. The exception is 1111 with an 8.8 percent solids discharge. This is probably due to the plant conditions and sampling.

Ash analysis of the refuse solids reveals several interesting points. First, the ratio of SiO_2 to Al_2O_3 is farily consistent between 2.0 to 2.5. Secondly, all the samples contain significant portions of iron oxide. It appears that all the plants are removing this from the coal in their attempt at reducing the sulfur content by removing pyritic sulfur. One interesting note is sample 1112 and its high concentration of calcium oxide and magnesium oxide. At these levels, the sample pH is not out of line with the other samples. Thus, these substances may not be free, but combined in a compound.

In conjunction with the solids analyses, the refuse liquid was analyzed and the results appear in Table V, Chemical Analyses of Supernatant Liquid from Fine Coal Refuse Samples. The major constituent in the supernatant is the total sulfur, reported as sulfate. Other important parameters are chloride, calcium,

sodium, magnesium, and hardness. These species are relatively soluble and probably reflect the geologic conditions at the time of the deposition of the coal-forming vegetation and subsequent sedimentation of the overburden.

One of the more important physical parameters of the fine refuse is the particle size consist and its ability to settle to higher solids concentrations. Table VI, Particle Size Analyses, tabulates the sieve analyses of the fine refuse solids as samples. All of the samples have greater than 40%, by weight, of particles finer than 100 mesh. More importantly, five of the nine samples (1104, 1110, 1111, 1113, and 1114) have 50% or greater minus 10 microns. In conjunction with these results, Table VII, Settling Test Summary, can be coupled to obtain an insight into the ability of these materials to be concentrated. This is important in thickener design, pond or impoundment design, and overall disposal considerations. Settling curves are used extensively in designing thickeners and most thickeners have up to 12 hours operating retention time. Using this as a guideline, review of the individual untreated settling curves in the appendix reveals that thickeners operating at a 5 percent inflow concentration will effectively concentrate the solids. Thus, properly designed, installed, and operated thickeners can help with the disposal problem by reducing the disposal volumes. For example, a comparison of the settled solids from the sampled materials and the 5 percent solids settling test for those plants having existing thickeners is:

	Settled Solids, % Solids	
Plant	As Received %	5% Initial Mixed Solids
1105	30.5	46.6
1106	20.9	50.5
1107	18.9	62.3
1112	30.0	59.9

As mentioned in the sampling section, 1106 may not be representative. Dravo's experience has shown that thickeners are consistently operated below the solids levels that they are capable of producing due to fears of pumping high solids. With today's slurry pumps, this is not a problem and higher solids thickener underflow operation should be investigated by the coal operator to help reduce overall fines disposal volume. This is clearly shown in the above table by noting the much higher level of solids achieved in the lab settling test. Realistically, 30 to 45% thickener underflow solids can be achieved and pumped.

As a further indication of solids concentration for reduction of disposal volume, a laboratory simulation of vacuum filtration was performed. Table VIII, Filter Leaf Test Summary, tabulates the data from this test. An important point to note is the prerequisite of a thickener prior to a vacuum filter in order to assure that the solids are as high as possible prior to

filtration. We employed a 35% initial solids concentration as a reasonable approximation of a thickener underflow. Using this starting point, all the samples filtered in the range of 60% to 70% solids, which is a realistic solids concentrate. Two other results are important: 1) dry cake yield and 2) filtrate solids. The filtrate solids indicate the build-up of fines in the preparation plant circuitry which eventually must be controlled so as not to choke the plant. The dry cake yield illustrates the variation in filter size that must be considered when designing a vacuum filter installation.

Because our laboratory program demanded large amounts of high solids cake, we employed a pilot rotary drum vacuum filter to generate the quantities needed. Table IX, Rotary Vacuum Filtration Summary, contains the results of the test. It should be noted that the filter feed was high solids settled slurry. Consequently, the filter cake solids were higher than those obtained from the filter leaf test. However, a very interesting point is that the dry cake yield is very close to the yield calculated in the filter leaf test. The values ranged from 5.5 lb/sq.ft./hour to 18.8 lb./sq.ft./hour. As can be seen from these two tests, off-the-shelf installation of filtration equipment without some degree of prior testing can greatly affect solids handling and disposal.

Engineering Data

Thus far, the discussion has dealt with the more common physical/chemical properties of the fines. The remainder of the discussion will center on the engineering properties of the fine coal refuse. Properties investigated and reported are:

1. Atterberg limits
2. Proctor density
3. Permeability
4. Direct shear
   a. Cohesion
   b. Angle of internal friction
5. Consolidation
6. Unconfined compressive strength
   a. Untreated
   b. Stabilized

Tables X and XI, Summary of Physical Properties Untreated Fine Coal Refuse, contain the information on Atterberg limits, specific gravity, effective grain size, settled solids, Proctor determination, permeability, direct shear, and consolidation.

Atterberg limit testing (indicative percent moisture levels) is generally considered qualitative and not completely indicative of a fine coal refuse since the particle size distribution employed is not the complete size consist. One level, the liquid limit, might be useful information in that it may indicate a critical

moisture content where the fluid-like properties of the fine refuse will predominate. Plastic limit is too qualitative to be of any real value.

The specific gravity values and size cut values are very interesting. The variation in specific gravity between plus 200 mesh and minus 200 mesh is important. Particle size analyses indicated that the dividing line between fine refuse and ultra-fine refuse is in the 100 to 200 mesh region; below 200 mesh being considered ultra-fine. Because the specific gravities are lower in the coarser fraction, this indicates that the coal is probably in the larger fraction and that modern cleaning techniques employed on this small size consist would probably yield a sizable coal fraction. Proctor density is another important value for consideration in the disposal of fines. By taking the dried fines, incrementally adding a known amount of water, and compacting this mixture in a specific volume with a constant amount of force, one obtains a curve of dry bulk density versus moisture content. The curve is similar to a parabola with the apex being the maximum bulk density obtainable with a minimum amount of moisture. Realistically, this value means that a cubic foot of refuse will contain the maximum amount of solids possible thus minimizing disposal volumes. Table X contains this Proctor data. However, this does not say anything about stability. Commonly employed dewatering devices, vacuum filters and centrifuges do not achieve these Proctor values either.

Table XI contains some very important data; permeability and cohesive strength of untreated fines. The permeabilities of all the settled solids are low, 10^{-5} to 10^{-6} cm/sec. The filter cake permeabilities are slightly lower than those of the settled solids and rightly so because of the energy used to increase the solids content; the lower permeabilities are due to less void space. Since strength, i.e., stability is of prime concern, the measure of cohesive strength is important. The data collected indicates that the untreated fines, whether settled slurry or filter cake, have virtually no strength. Values reported are all less than 1 psi cohesive strength.

Table XII, Summary of Laboratory Strength Parameters - Consolidation Tests - Untreated Fine Coal Refuse, contains an important point. That is, the fines are not compressible. The compression index, C, is a ratio of the void ratio and applied pressure. High values, greater than .5, are indicative of materials that compress whereas small numbers, .10 to .20, are related to noncompressible materials. Secondly, the low recompression index, C_{cr}, indicates little or virtually no rebound of the slurry when the load is released. A possible relationship may exist between the compression index, Btu/lb. value, and size consist. Another important fact, the low cohesive strengths of the untreated fines, is shown in Table XIII, Summary of Laboratory Strength Parameters - Direct Shear Tests - Untreated Fine Coal Refuse. This is true whether the fines are a settled solids or a highly dewatered filter cake. In both cases, the fines have

less than 1 psi cohesive strength. Recalling that the fines are noncompressible, one sees that large impoundments of fine refuse are only as safe as the impoundment itself. If released, the material will not hold together and will flow when stresses are applied. Flow movement can be caused by forces as small as gravitational forces.

Stabilization Data

We have shown that untreated fine coal refuse lacks stability and strength. The objective of the study is to improve the strength with the addition of Portland Type I cement, hydrated lime, or Calcilox additive. Stabilization is now defined as the gain of unconfined compressive strength. Dravo Lime Company possesses expertise in this technology and has developed a method of adding stabilization chemicals to the slurry as a percentage of dry slurry solids. To be effective, economically and technically, we have shown that the slurry solids concentration must be greater than 25%. Solids levels between 25%-35% would be representative of thickener underflow discharges, whereas filter cake solids would be indicative of mechanically dewatered slurries. Depending on disposal mode (ponds, impoundments, or high solids cake) chemical additive dosages fall within the range of 5% to 15%, by dry weight of the slurry solids. The rate of strength gain is monitored over time and plots of unconfined penetration resistances (tons per square foot) versus time (days) are obtained and can be used to determine optimum dosages for various strength developments. The test method is described in the appendix with the accompanying plots.

More accurate information is obtained at selected stabilization times by performing unconfined compressive tests on the test specimens. This test gives an accurate estimate of the strength of the material since it has no lateral support to increase the normal resistance. A relationship exists between unconfined compressive strength (shear strength) and cohesive strength. Shear strength is one-half of the unconfined strength, and shear strength is related to cohesive strength as determined in the direct shear test. Table XIV, Summary of 40-Day Unconfined Compression Strength, tabulates the pertinent data. Forty days was arbitrarily chosen to meet the timing constraints of the study and was an appropriately long time to produce measurable strengths. Since we are dealing with chemical reactions, temperature should have an effect. The summer time temperature selected was 72°F, while 55°F was selected as a yearly average temperature. A lower temperature, 39°F, was tested in rate monitoring as indicative of severe weather conditions. Unconfined compression data at 39°F or below were not obtained since results would only reflect freezing and not chemical stabilization.

Reviewing Table XIV, several specific results are apparent:

1. With the exception of three points, the untreated underflow and filter cake do not possess any measurable strength.

2. 5% Portland Type I cement addition improves filter cake strengths.

3. 5% lime is effective on filter cake solids.

4. 5% Calcilox A is effective on slurries and filter cakes, but slurries may be dependent upon slurry solids.

5. 5% Calcilox B is not as effective as Calcilox A.

6. 10% Portland Type I cement is effective on filter cakes.

7. 10% lime is only effective on filter cakes.

8. 10% Calcilox A and B are effective on slurries and filter cakes.

9. 15% Portland Type I cement is slightly effective on slurries.

10. 15% lime is not effective on slurries but may be effective on filter cakes.

11. 15% Calcilox A and B are effective on slurries and high solids cakes.

NOTE: Calcilox A and B vary only in the percent CaO.

Some general conclusions are:

1. Chemical stabilization of fine coal refuse is effective.

2. Calcilox is superior to lime and Portland Type I cement for slurries and filter cakes.

3. Calcilox is effective on 25% to 35% slurries and filter cake materials.

4. Portland Type I cement is not effective on 25% to 35% solid slurries, but effective on filter cake materials.

5. Lime is not effective on 25% to 35% solid slurries but effective on filter cake materials.

6. Solids level is an important consideration for chemical stabilization.

7. Temperature has an effect on stabilization; the higher the temperature, the more rapid the strength development.

It should also be emphasized that these unconfined compression data are only singular points. No duplication of test specimens occurred and certain inconsistencies are present in the data points although the method was employed correctly. For example, one would expect higher strengths at 72°F than at 55°F. Generally, this is true, but some data points do not show this. Also, higher solids should produce high strengths. Again, some points appear to show the reverse.

The unconfined compression data are very valuable; but other, less precise information has also been gathered on the role of stabilization. This is presented in Tables XV and XVI, Stabilization Rate, where a 90-day stabilization period was monitored by a hand-held penetrometer (Model CL-700, Soiltest, Inc.).* In Table XV, the days to reach 2 TSF are presented. This penetration resistance (2 TSF or 27.8 psi) is ample for handling by normal construction means. Table XVI presents data on days to reach 4.5 TSF. This value may be excessive and lesser strengths are adequate for handling. Since the Portland Type I cement and Calcilox reactions are cementitious in nature, it may be advisable to handle a fine refuse at the minimum handleable strength and place it in its final disposal site. At this site, the chemical reaction will continue but at a slower rate. Final strengths are nearly identical to those attained from non-disturbed samples. Another data point that has been included in these tables is a reading at 39°F and illustrates the rate difference between 39°F and 55°F or 72°F. The difference between 55°F and 72°F is not as promounced with this method as is shown in the unconfined results due to the accuracy of the unconfined test method.

These rate measurements illustrate results similar to those of the unconfined tests. Generally, they are:

1. Temperature affects the rate of stabilization, the higher the temperature, the faster the reaction.

2. Overall, Calcilox is superior to lime and Portland Type I cement in slurries and filter cake applications.

3. Lime additions appear to give better results than Calcilox or Portland Type I cement in certain instances. Comparison with unconfined strengths should be made for realistic data.

4. Solids level affects chemical stabilization. The higher the solids, the faster the stabilization.

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*The monitoring method conducted with a hand-held penetrometer on small samples is somewhat inaccurate. That is, the sidewalls of the container exert a positive influence on the result. Secondly, the error in the penetrometer itself is roughly ± 0.5 TSF.

Data Correlation

Because of the scope of the study, the test results were, of necessity, obtained from single sample testing. This condition precludes an in-depth analysis of the test results. However, there appears to be a definite relationship in the physical properties of the various coal refuse samples. This relationship can be expressed by ranking the coal refuse samples in an order of high to low, or low to high, depending upon the results from the various tests and how one physical property relates to another.

When the graphs of the particle size analysis were combined, they delineated a uniform broad band (Table XVII-A) covering about 50% of the finer, by-weight, scale. This combined graph showed that there were distinctive differences in particle size from sample to sample.

The particle size of a particulate solid is a determining factor in practically all physical property tests that were conducted. Large particles increase permeability, settling, cohesion and filterability and decrease compaction, liquid limits, and optimum water contents.

As a first ranking, the refuse samples were ranked according to the percent retained on a 200 mesh sieve from low to high. The 200 mesh division was chosen because specific gravities were determined on the material as a whole and on the -200 mesh material. Calculations to determine the specific gravities of the +200 mesh material showed them to be in the coal range indicating the +200 mesh material was mostly coal.

From the results of eight other tests, the samples were ranked from low to high or high to low depending upon the effect the particle size would have on the physical properties, and these rankings were compared with the particle size ranking.

The samples were then re-ranked according to their average ranking for all of the tests and separated into three groups with three samples in a group (Table XVII-B). Over 65% of the test results agreed with this group ranking.

With the use of a single test value, there are obviously going to be some discrepancies and various preparation plant processes, such as mixing with oil in the froth flotation process, would also have an adverse effect. Sample 1107 in particular, although ranked sixth in the average ranking, ranked high and low in the individual tests, thus causing a lower percentage of agreement. This non-conformity may have been due to the difficulty in sampling from an almost inaccessible sampling point.

Since there appeared to be some obvious rankings or correlation, a further look at some of the data was undertaken with the aid of a time share computer package called "Procap" offered by Compuserve, Columbus, Ohio. This program performs single step regression analyses on the variables and ranks them in order of their importance in defining the dependent variable. The dependent variable that was chosen as most important was 40-day unconfined strength.

In the first run utilizing Procap, certain fine refuse solids physical/chemical characteristics were analyzed with the 40-day unconfined strength of a 35% slurry treated with 15% Calcilox A and cured at 72°F. Independent variables were chosen as volatile matter, ash, percent carbon, BTU/lb., 50% weight diameter, particle size, settling rate per day, and overall solids specific gravity. After numerous runs with various combinations and eliminations of variables, it was concluded that settling rate per day and specific gravity had the greatest effect on stabilization strength. Since the 40-day strengths at an initial 35% solids are low, a comparison of 40-day strengths on filter cakes was made. The variables tested were ash, volatile matter, carbon, BTU/lb., percent solids, 50% weight diameter particle size, and solids specific gravity. The dependent variable was again 40-day strength at filter cake solids with 10% Calcilox A addition and cured at 72°F. Much to our chagrin, no significant correlations were obtained with the filter cake.

Because the computer program is capable of accepting many independent variables, more physical/chemical data were inputed with the independent variable still being the 35% solids mixture with 10% Calcilox A additive. Twelve independent variables were tested resulting in less of a correlation than the first run with only seven independent variables. New independent variables were selected and tested against 40-day strength of a filter cake with 10% Calcilox additive. Again, no significant correlation was evident.

Intuitively, these results are not acceptable because experience indicates that there are some correlations. It is felt that unconfined compressive strengths may be in error since they are singular points without any duplication. In reviewing the unconfined data, there are obvious unexplained results although the test method is correct. The sample 1107, the 10% lime addition to filter cake is erroneous. The 55°F unconfined compression value is 290.9 psi while the 72°F was only 15.2 psi. Comparing the other 10% lime to filter cake values for the other samples, one sees that the 290.9 psi point is way out of range. Other questionable points probably exist and if used in a sensitive statistical analysis, would produce invalid results. It is suspected that this is the case in our computer analyses since the ranking system produced reasonable results. More accurate data points are needed to develop statistically valid correlations.

Patents, Inventions, and Disclosures

Based on prior patents and the state-of-the-art, we do not believe that this study produced any new information or ideas of a proprietary or patentable nature.

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TABLE I

SAMPLE PREPARATION PLANT SUMMARY

Plant Designation	State	County	Seam	Mine Type	Coal Application	Prep Plant Capacity (TPH)	Clean Coal (TPY)	Prep Plant Operating Equipment													
								Screens	Crusher	Jigs	Deister Tables	Picking Tables	Heavy Media	Froth Flotation	Cyclones	Centrifuges	Magnetic Separator	Filters	Dryers	Refuse Thickeners
1104	Pa.	Allegheny	Pittsburgh	Strip	Steam	350	600,000	•	•		•		• (Drum)		•	•	•			
1105	Pa.	Allegheny	Upper Freeport	Deep	Steam	400	800,000		•		•			•	•	•		•	•	•
1106	Pa.	Somerset	Lower Kittanning B	Deep	Metallurgical	350	600,000	•					•	•	•	•	•	•		•
1107	Pa.	Greene	Pittsburgh	Deep	Metallurgical	950	1,250,000	•				•	•	•			•	•		
1110	W.Va.	Fayette	Coalburg Eagle No. 2 Gas Powellton Five Block	Deep and Strip	Metallurgical and Steam	600	800,000	•	•		•		•	•	•		•	• (R)	•	•
1111	W.Va.	Logan	Winifred Chilton Cedar Grove	Deep	Metallurgical	800	1,000,000	•	•	•	•		•	•	•	•	•		•	•
1112	Va.	Buchanan	Pocahontas #3	Deep	Metallurgical	625	1,250,000	•	•		•		•	•		•	•	• (R)	•	•
1113	Ind.	Warrick	Indiana V	Strip	Steam	1,800	3,400,000		•	•					(W)	•				
1114	Ill.	Williamson	Illinois 6	Strip	Steam	900	700,000	•	•	•			•			•	•			

NOTE: (•) Coal Cleaning Equipment used
(R) Similar Refuse Equipment used
(W) Water Only

TABLE II

SAMPLE PREPARATION PLANT DISPOSAL SUMMARY

Plant Designation	Disposal Summary
1104	No thickeners are employed, plant discharge is pumped to two large abandoned strip pits. A single point discharge fills one pit while overflow cascades into adjoining pit which serves as final settling pond. The pH of final overflow is acidic and is adjusted prior to reuse in prep plant circuit.
1105	The thickener underflow is pumped to one of three large settling ponds. A single point discharge fills one pond while others are being excavated. The supernatant is discharged and the settled solids excavated and saved for sale or reprocessing.
1106	The thickener underflow is disposed of either into two small settling ponds or injected back into the mine for placement and disposal. Because of the handling problems associated with the settling ponds and above ground disposal, mine disposal system is preferred.
1107	The thickener underflow is pumped to a large, permanent coarse refuse impoundment. The supernatant overflows into a clarification pond for discharge.
1110	The thickener underflow is filtered on vacuum disc filters with transport of the filter cake on the coarse reject belt. The combined refuse is compacted with a dozer.
1111	The thickener underflow is pumped to a series of permanent settling ponds that are filled through a single point discharge. The waste remains in these ponds and the supernatant is discharged to receiving streams.
1112	The thickener underflow is vacuum disc filtered and the resultant cake is combined with the coarse on an aerial tram. The trammed material is spread and compacted with a dozer at the disposal site.
1113	The plant discharge is pumped to abandoned strip pits and the supernatant cascades one into another for recycle back into the prep plant. The settled solids are covered with overburden.
1114	The plant discharge flows by gravity into abandoned strip pits and the supernatant cascades one into the other for reuse back into the prep plant. The settled solids are covered with overburden.

TABLE III

LABORATORY TESTING PROGRAM OUTLINE

I. Index Properties

A. Wet Screen Analysis (to 10 Microns)

B. Settling Test Starting at:

1) 5% Solids

2) 35% Solids

3) 35% Solids + 10% Calcilox A

4) 35% Solids + 10% $Ca(OH)_2$

5) 35% Solids + 10% Portland Cement Type I

C. Liquid and Plastic Limit

D. Specific Gravity

1) Entire Sample

2) -200 Mesh Material

E. Chemical Analyses

1) Refuse Solids

2) Supernatant

II. Engineering Properties

A. Permeability

1) Settled Slurry

2) Filter Cake

B. Consolidation

1) Settled Slurry

C. Penetration

1) Compacted Filter Cake

2) Compacted Filter Cake (Lower Water Content)

3) Settled Slurry

D. Direct Shear @ 1 psi

1) Settled Slurry

2) Filter Cake

III. Filtration

A. Filter Leaf

B. Rotary Drum

IV. Stabilization Tests

Dosages	Solids Level 25%	35%	Filter Cake
A. Untreated	*x	*x	*x
B. 5% Portland Type I	-	*x	*x
5% $Ca(OH)_2$	-	*x	*x
5% Calcilox A	-	*x	*x
5% Calcilox B	-	*x	-
C. 10% Portland Type I	*x	*x	*x
10% $Ca(OH)_2$	*x	*x	*x
10% Calcilox A	*x	*x	*x
10% Calcilox B	-	*x	-
D. 15% Portland Type I	*x	*x	-
15% $Ca(OH)_2$	*x	*x	-
15% Calcilox A	*x	*x	-
15% Calcilox B	-	*x	-

x = Mixed and monitored by penetrometer at 39°F, 55°F and 72°F for 90 days.

* = 40-Day unconfined tests performed at 55°F and 72°F

TABLE IV

CHEMICAL ANALYSES OF SOLIDS FROM FINE COAL REFUSE SAMPLES[1]

(Analyses Reported in Weight % except BTU and pH)

Analysis of Refuse	Sample Number								
	1104	1105	1106	1107	1110	1111	1112	1113	1114
Moisture	0.76	0.15	0.22	0.58	0.85	0.60	0.35	1.12	1.08
Ash	58.86	29.36	23.59	38.58	35.82	44.00	25.12	47.32	45.83
Volatile Matter	17.82	27.67	17.32	24.06	21.63	20.06	19.10	20.79	19.81
Fixed Carbon	22.56	42.82	58.87	36.78	41.70	35.34	55.43	30.77	33.28
Sulfur, Total	1.53	2.65	1.62	2.29	0.61	0.65	0.75	2.81	1.98
Pyritic Sulfur	1.00	2.27	0.96	1.64	0.20	0.40	0.50	1.90	1.19
Sulfate Sulfur	0.36	0.09	0.21	0.07	0.00	0.04	0.00	0.23	0.18
Organic Sulfur	0.17	0.29	0.47	0.58	0.41	0.21	0.25	0.68	0.61
BTU/Lb.	5294	10416	11680	8640	9078	7814	10844	6415	6901
Percent Solids	10.6	30.5	20.9	18.9	24.2	8.8	30.0	14.9	15.2
pH	4.4	7.7	8.1	7.9	7.9	8.0	7.8	8.0	7.7
Analysis of Ash									
SiO_2	60.79	45.88	50.68	51.14	58.05	58.35	39.50	57.15	63.02
Al_2O_3	24.41	20.93	25.12	21.07	26.65	24.85	18.62	24.28	17.56
TiO_2	1.26	0.96	1.60	1.10	1.23	0.99	0.81	0.88	0.81
Fe_2O_3	6.81	12.85	12.36	12.65	5.55	6.05	6.96	8.36	5.94
CaO	1.12	8.50	3.57	5.95	1.52	1.82	17.08	2.95	5.98
MgO	1.07	0.81	0.72	1.23	1.41	1.74	9.45	1.44	1.43
Na_2O	0.38	0.45	0.29	0.42	0.42	0.47	0.39	0.45	0.47
SO_3	0.88	6.07	2.36	2.20	0.84	1.18	4.61	1.30	2.06
P_2O_5	0.11	0.14	0.49	0.18	0.01	0.02	0.01	0.13	0.05
K_2O	2.97	2.26	1.88	2.47	4.00	4.40	2.51	3.02	2.56

[1] As Received

TABLE V

CHEMICAL ANALYSES OF SUPERNATANT LIQUID FROM FINE COAL REFUSE SAMPLES[1]

(Analyses Reported in mg/L except pH and Specific Conductance)

Analysis	SAMPLE NUMBER								
	1104	1105	1106	1107	1110	1111	1112	1113	1114
pH	4.4	7.7	8.1	7.9	7.9	8.0	7.8	8.0	7.7
Alkalinity	0	120	68	114	134	173	113	103	46
Sp. Conductance ($\frac{\mu mhos}{cm}$)	2670	3750	2670	1680	680	1480	1520	1220	1970
Filterable Residue (TDS)	4540	5330	3810	2280	590	1580	1360	1620	3440
Total S (as $SO_4^=$)	3010	2680	2530	1370	280	920	180	980	2260
Chloride	12	670	13	66	39	49	610	53	18
Total Iron	0.2	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1	< 0.1
Calcium	650	470	560	300	100	120	140	140	440
Sodium	215	965	347	290	80	300	290	211	225
Potassium	8	11	6	5	6	10	4	7	9
Magnesium	250	90	100	29	11	27	25	56	172
Manganese	30	2.6	0.6	0.5	0.4	0.3	< 0.1	1	14
Total Hardness (as $CaCO_3$)	2660	1540	1800	8610	3000	10010	4000	6010	18020

[1]As Received

TABLE VI

PARTICLE SIZE ANALYSIS [1]

PERCENT RETAINED

(WEIGHT %)

Sample No.	U.S. Standard Sieve No.							Microns		
	16	30	50	100	200	325	400	20	10	-10
1104	2.0	5.0	7.7	8.3	8.5	6.0	2.8	9.0	18.6	32.1
1105	0.3	2.8	16.5	19.5	16.8	6.8	29.8	1.5	3.1	2.9
1106	1.8	8.9	20.2	18.0	15.4	6.2	16.5	2.7	4.8	5.6
1107	4.9	17.0	21.1	13.7	9.4	3.9	19.6	1.4	3.3	5.7
1110	0.1	1.3	3.8	6.8	13.2	8.5	5.0	9.8	22.5	29.0
1111	0.0	1.9	6.7	10.1	14.3	9.5	3.5	8.3	18.5	27.2
1112	1.4	13.2	25.7	17.8	13.0	7.9	3.2	4.0	8.5	5.3
1113	0.2	1.5	8.0	11.6	10.5	6.2	2.6	6.5	17.1	35.8
1114	0.6	2.6	7.8	11.7	13.8	11.0	4.7	7.3	18.3	22.2

[1] As Received

TABLE VII

SETTLING TEST SUMMARY

SAMPLE NO.	5% Solids No Additive		35% Solids No Additive		35% Solids 10% $Ca(OH)_2$		35% Solids 10% Calcilox A		35% Solids 10% Portland Cement	
	Time Days	Solids Final %	Time Days	Solids Final %	Time Days	Solids Final %	Time Days	Solids Final %	Time Days	Solids Final %
1104	1.1	44.4	5.1	55.9	2.7	39.8	1.2	41.1	0.1	37.7
1105	0.2	46.6	0.9	59.8	0.8	59.2	0.2	57.6	0.8	43.1
1106	0.1	50.5	0.5	59.5	2.9	50.5	0.5	53.4	0.2	47.7
1107	0.6	62.3	2.0	61.4	0.7	39.9	0.3	42.0	1.8	49.3
1110	2.0	45.1	6.1	52.0	2.3	42.3	3.0	42.1	0.3	37.9
1111	2.0	51.7	4.9	55.0	3.0	42.6	1.0	43.4	0.2	38.6
1112	0.9	59.9	0.8	62.2	0.9	61.8	0.3	61.3	0.6	54.1
1113	2.3	40.3	3.2	42.3	3.2	43.5	0.9	38.6	0.2	37.6
1114	1.3	35.5	6.0	47.4	2.7	41.9	0.9	39.1	0.9	37.7

TABLE VIII

FILTER LEAF TEST SUMMARY

Slurry Solids. . . . 35%

Filter Medium. . . . Eimco Polypropylene 853F

Form Vacuum . . . . 24 Inches of Mercury

Dry Vacuum . . . . 24 Inches of Mercury

Dry Air Velocity . .0.5 Cubic Feet per Minute

Sample No.	Form Time (Sec.)	Dry Time (Sec.)	Dry Cake Yield (Lb./Sq.Ft./Hour)	Filter Cake Solids (%)	Filtrate Yield (Gal./Sq.Ft./Hour)	Filtrate Solids (%)
1104	15	30	9.9	67.3	3.8	.30
1104	45	90	5.1	68.6	2.3	.47
1105	15	30	12.2	63.9	5.2	.49
1105	45	90	10.5	67.6	4.6	.48
1106	15	30	7.5	65.5	2.8	.54
1106	45	90	5.5	67.8	3.8	.49
1107	15	30	5.0	69.1	2.5	.49
1107	45	90	3.4	75.0	2.3	.44
1110	15	30	11.0	62.4	1.1	.38
1110	45	90	8.5	64.2	2.0	.27
1111	15	30	15.2	64.6	2.3	.38
1111	45	90	6.7	65.0	2.4	.40
1112	15	30	14.4	69.2	8.5	.29
1112	45	90	9.2	70.5	6.0	.26
1113	15	30	7.5	64.8	1.7	.13
1113	45	90	4.3	65.1	1.1	.38
1114	15	30	28.0	66.9	2.3	.38
1114	45	90	18.7	69.9	2.0	.43

TABLE IX

ROTARY VACUUM FILTRATION SUMMARY

Filter Medium:. . . . Eimco Polypropylene 853F

Filter Area . . . . . 4.7 Square Feet

Form Vacuum . . . . . 20 Inches of Mercury

Dry Vacuum . . . . . 7 Inches of Mercury

Dry Air Velocity. . . 4 Cubic Feet per Minute

Sample No.	Slurry Solids (%)	Drum Speed (M.P.R.)(1)	Form Time (Sec.)	Dry Time (Sec.)	Dry Cake Yield Lb./Sq.Ft./Hour	Filtrate Yield Gal./Sq.Ft./Hour	Filter Cake Solids (%)
1104	51.6	6	135	180	9.8	.7	75.0
1105	59.9	5	113	150	13.2	.45	72.0
1106	62.4	5	113	150	8.5	.39	81.2
1107	65.0	5	113	150	8.5	.32	81.5
1110	49.4	8	180	240	11.1	.81	70.3
1111	40.8	6	135	180	7.7	1.02	73.7
1112	56.7	4	90	120	12.7	.80	81.0
1113	43.3	8	180	240	5.5	.58	70.5
1114	43.8	3	68	90	18.8	2.00	71.6

(1) - Minutes Per Revolution

TABLE X

SUMMARY OF PHYSICAL PROPERTIES

UNTREATED FINE COAL REFUSE

Sample No.	Atterberg Limits			Specific Gravity			Grain Size		Solids Content			Proctor Determination	
									Settled Slurry				
	Liquid Limit (%)	Plastic Limit (%)	Plasticity Index	As Received	+ 200 MESH[2]	- 200 MESH	Effective Size, D_{10} (mm)	Coefficient of Uniformity (Cu)	5% Solids (1)	35% Solids (1)	Filter Cake (%)	Maximum Density (Lb./Ft.3)	Optimum Moisture (%)
1104	29.6	24.4	5.2	2.09	1.90	2.18	.006 *	7.32*	44.4	55.9	75.0	86.0	16.6
1105	25.8	NP	-	1.53	1.38	1.72	.037	3.95	46.6	59.8	72.0	64.3	23.9
1106	22.4	NP	-	1.58	1.50	1.74	.018	11.11	50.5	59.5	81.2	72.1	14.6
1107	25.5	24.1	1.4	1.81	1.73	1.97	.032	10.31	62.3	61.4	81.5	81.6	14.5
1110	34.5	33.2	1.3	1.65	1.23	1.79	.007 *	5.00*	45.1	52.0	70.3	67.7	22.0
1111	34.2	33.2	1.0	1.76	1.32	1.98	.006 *	8.33*	51.7	55.0	73.7	73.2	18.8
1112	24.1	NP	-	1.34	1.25	1.55	.016	19.35	59.9	62.2	81.0	71.0	15.0
1113	36.2	29.7	6.5	1.80	1.05	2.15	.005 *	7.80*	40.3	42.3	70.5	73.9	23.3
1114	37.4	34.9	2.5	1.83	1.33	2.12	.006 *	10.30*	35.5	47.4	71.6	78.0	17.0

NOTE: NP - Non-Plastic
* - Approximate Value
(1) - Initial Mixed Solids Content
(2) - Calculated Value

TABLE XI

SUMMARY OF PHYSICAL PROPERTIES
UNTREATED FINE COAL REFUSE

Sample No.	Permeability				Direct Shear										Consolidation
	Settled Slurry		Filter Cake		Settled Slurry					Filter Cake					
	cm/sec.	Solids[1] (%)	cm/sec.	Solids (%)	Consolidated Density (Lb/Ft^3)	Degree of Saturation (%)	ϕ^2	Cohesion (psi)	Solids (%)	Consolidated Density (Lb/Ft^3)	Degree of Saturation (%)	ϕ^2	Cohesion (psi)	Solids (%)	Compression Index (C_c)
1104	6.0×10^{-6}	71.7	5.1×10^{-7}	76.8	69.6	84.7	10°	0.018	73.7	74.8	90.7	22°	0.200	75.4	0.19
1105	1.0×10^{-5}	73.1	4.1×10^{-6}	77.0	66.4	76.7	51°	0.218	78.4	50.6	60.2	36°	0.309	71.7	0.12
1106	7.4×10^{-6}	76.0	4.8×10^{-6}	79.6	71.1	98.9	53°	0.173	80.5	56.1	51.3	30°	0.182	80.2	0.09
1107	2.6×10^{-6}	79.6	1.3×10^{-6}	82.5	75.8	78.0	34°	0.036	80.3	79.2	72.2	38°	0.791	83.3	0.11
1110	4.4×10^{-6}	65.4	1.6×10^{-6}	73.0	58.1	94.2	20°	0.073	69.5	62.1	98.7	29°	0.045	71.8	0.15
1111	4.1×10^{-6}	67.3	1.4×10^{-6}	75.9	65.2	97.8	37°	0.045	72.6	69.9	88.9	42°	0.245	77.8	0.17
1112	1.9×10^{-5}	71.2	6.2×10^{-6}	82.0	62.1	98.4	22°	0.327	79.7	68.6	100.0	28°	0.255	84.6	0.15
1113	4.2×10^{-6}	64.9	2.0×10^{-7}	74.5	62.1	100.0	11°	0.100	68.7	52.1	100.0	14°	0.218	70.8	0.19
1114	5.5×10^{-6}	65.0	8.1×10^{-7}	74.0	68.2	100.0	8°	0.055	72.6	68.0	89.5	21°	0.082	72.8	0.18

[1] Solids = % Dry Wgt.

[2] Angle of Internal Friction

[3] Settled Slurry

TABLE XII

SUMMARY OF LABORATORY STRENGTH PARAMETERS
CONSOLIDATION TESTS
UNTREATED FINE COAL REFUSE

Sample No.	Water Content[1]		Dry Unit Weight		Initial Void Ratio	Initial Compression Index (C_{ci})	Compression Index (C_c)	Recompression Index (C_{cr})
	Before Test (%)	After Test (%)	Before Test (Lb./Ft.^{3})	After Test (Lb./Ft.^{3})				
1104	47.9	21.2	88.0	107.4	1.10	.102	0.19	0.030
1105	35.7	24.7	79.1	86.1	0.78	.050	0.12	0.020
1106	24.4	13.6	79.3	86.8	0.40	.042	0.09	0.015
1107	22.4	15.5	100.2	106.2	0.56	.015	0.11	0.021
1110	59.0	32.1	64.8	78.0	0.99	.084	0.15	0.035
1111	53.4	31.6	71.2	83.0	0.97	.070	0.17	0.030
1112	39.1	21.2	60 1	69.0	0.51	.065	0.15	0.015
1113	66.1	29.9	67.6	86.5	1.20	.113	0.19	0.040
1114	56.3	30.4	72.7	87.1	1.10	.111	0.18	0.035

[1] Water Content (%) = $\frac{\text{Wgt. of Water}}{\text{Wgt. of Dry Solids}}$

TABLE XIII
SUMMARY OF LABORATORY STRENGTH PARAMETERS
DIRECT SHEAR TESTS
UNTREATED FINE COAL REFUSE

Sample No.	Preconsolidation Pressure (psi)		Consolidating Pressure (psi)		Shear Stress (psi)		Dry Wt. After Test (Lb./Ft^3)		Water Content After Test (%)[1]		Degree of Saturation (%)		Solids Content[2] - (%) Before Test		Solids Content[2] - (%) After Test		Unit Cohesion (psi)		Internal Friction Angle (Degrees)	
	SS	FC	SS	FC	SS	FC	SS	FC	SS	FC	SS	FC	SS	FC	SS	FC	SS	FC	SS	FC
1104	.9	.9	.18 .36 .55 .73	.18 .36 .55 .73	.05 .07 .10 .14	.28 .35 .44 .51	69.6	74.8	35.6	32.6	84.7	40.7	68.6	75.0	73.7	75.4	.018	.200	10	22
1105	.9	.9	- .36 .55 .73	.18 .36 .55 .73	- .66 .85 1.10	.44 .57 .7 .84	66.4	50.6	27.5	39.5	74.7	60.2	72.8	72.0	78.4	71.7	.218	.309	51	36
1106	.9	.9	.18 .36 .55 .73	.18 .36 .55 .73	.40 .66 .88 1.24	.29 .39 .50 .61	71.1	56.1	24.2	24.7	98.9	51.3	74.5	81.2	80.5	80.2	.173	.182	53	30
1107	.9	.9	.18 .36 .55 .73	.18 .36 .55 .73	.15 .26 .41 .53	.79 1.10 1.23 1.36	75.8	79.2	24.6	20.1	78.0	72.2	77.7	81.5	80.3	83.3	.036	.791	34	38
1110	.9	.9	.18 .36 .55 .72	.18 .36 .55 -	.15 .21 .32 .35	.15 .25 .36 -	58.1	62.1	43.8	39.2	94.2	98.7	56.1	70.3	69.4	71.8	.073	.045	20	29
1111	.9	.9	.18 .36 .55 .72	.18 .36 .55 .73	.14 .37 .48 .62	.41 .55 .73 .96	65.2	69.9	37.1	34.1	97.8	88.9	60.8	73.7	72.4	77.8	.045	.245	37	42
1112	.9	1.04	.18 .36 .55 .72	.09 .27 .45 .64	.32 .48 .55 .64	.26 .40 .50 .60	62.1	68.6	25.4	18.2	98.4	100	69.1	81.0	79.4	84.6	.327	.255	22	28
1113	.9	.9	.18 .36 .55 .72	.18 .36 .55 .73	.14 .17 .21 .25	.25 .32 .36 .42	62.1	62.1	45.5	41.2	100	100	56.4	70.5	68.7	70.8	.100	.218	11	14
1114	.9	.9	.10 36 .55 .72	- .36 .55 .73	.07 .11 .14 .16	- .23 .30 .36	68.2	68.0	37.7	37.4	100	89.5	58.2	71.6	72.6	72.8	.045	.082	8	21

Definition of:

[1] % Water = weight of water / weight of dry solids

[2] Solids = % Dry Weight

NOTE: SS = settled solids
FC = filter cake

TABLE XIV
SUMMARY OF 40-DAY UNCONFINED COMPRESSION STRENGTH
(PSI)

Treatment		Sample Number																	
		1104		1105		1106		1107		1110		1111		1112		1113		1114	
Additive	Mixed Solids %	55°(1)	72°	55°	72°	55°	72°	55°	72°	55°	72°	55°	72°	55°	72°	55°	72°	55°	72°
Untreated	25	*(2)	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
	35	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
	FC	*	*	4.7	6.6	*	*	*	*	*	*	*	*	*	5.1	*	*	*	*
5% Portland Type I	35	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
	FC	103.1	95.9	83.1	85.0	90.6	73.9	112.1	123.2	31.7	18.7	62.2	67.6	62.1	50.5	47.7	60.4	57.7	67.1
5% Lime	35	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
	FC	30.0	37.2	24.2	23.1	15.7	20.0	24.6	23.2	*	7.6	16.9	*	3.5	8.5	8.7	9.6	14.4	15.6
5% Calcilox A	35	*	*	10.6	8.8	5.8	8.5	2.6	10.0	0.8	0.8	0.8	1.6	4.9	4.8	*	1.4	1.7	2.0
	FC	52.3	78.6	123.5	124.9	80.4	80.3	117.1	218.2	34.2	81.3	117.7	50.7	86.0	98.5	44.8	106.9	53.2	89.1
5% Calcilox B	35	*	*	9.8	7.2	13.4	4.9	4.7	7.5	*	1.4	0.8	2.6	6.9	10.2	*	1.5	*	2.0
10% Portland Type I	25	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
	35	1.3	1.6	*	0.8	2.6	2.8	*	*	*	*	*	*	*	*	0.2	0.9	*	*
	FC	113.6	141.3	158.8	165.3	130.1	141.0	277.8	76.1	111.0	115.5	172.3	141.5	88.4	159.4	194.1	160.9	135.1	145.4
10% Lime	25	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
	35	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
	FC	32.4	39.8	17.7	12.6	20.3	22.2	290.9	15.2	13.7	16.4	21.3	13.6	20.7	13.3	13.3	14.6	9.7	16.1
10% Calcilox A	25	5.4	6.1	45.1	39.4	18.1	19.7	216.4	20.6	5.8	5.4	6.5	9.0	7.1	7.7	2.6	3.7	4.9	4.7
	35	7.5	15.1	32.8	27.0	25.9	33.9	20.7	38.9	2.2	10.8	3.5	14.1	6.9	4.5	2.5	8.4	4.1	4.4
	FC	273.7	368.6	190.7	188.5	295.5	494.4	252.1	233.7	70.0	120.0	212.4	116.6	85.8	69.9	152.9	231.2	207.0	224.5
10% Calcilox B	35	9.2	10.3	28.6	37.5	37.5	36.1	13.0	32.8	4.9	19.5	3.4	12.2	13.3	33.7	2.2	16.4	4.0	6.8
15% Portland Type I	25	*	*	*	*	*	1.9	2.6	*	*	*	*	*	*	*	*	*	*	*
	35	3.6	4.5	*	2.2	8.1	3.6	*	*	0.8	1.9	*	*	*	*	1.3	1.9	*	*
15% Lime	25	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
	35	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*	*
15% Calcilox A	25	13.4	15.4	58.7	31.0	51.0	80.6	99.3	47.7	6.8	12.1	7.7	15.5	3.1	6.6	8.4	10.3	12.2	11.6
	35	16.5	24.4	69.5	30.2	55.3	59.4	28.3	35.7	4.1	17.1	9.8	21.0	7.6	13.3	11.8	24.2	4.5	15.0
15% Calcilox B	35	29.4	35.9	32.4	86.1	49.2	80.3	54.8	87.9	15.1	34.4	7.2	26.4	19.9	39.3	12.2	39.5	4.5	24.0

(1) Curing temperature measured in degrees Fahrenheit.
(2) * Indicates specimen did not have a measurable strength at 40 days.

TABL

STABILIZA
DAYS TO R

Treatment		Sample																	
Additive	Mixed Solids (%)	Solids Content[5] (%)	1104 39°[4]	1104 55°	1104 72°	Solids Content (%)	1105 39°	1105 55°	1105 72°	Solids Content (%)	1106 39°	1106 55°	1106 72°	Solids Content (%)	1107 39°	1107 55°	1107 72°	Solids Content (%)
Untreated	25	52.1	*[2]	*	*	55.4	*	*	*	56.5	*	*	*	61.7	*	*	*	49.7
	35	55.9	*	*	*	59.8	*	*	*	59.5	*	*	*	61.4	*	*	*	52.0
	FC	75.0	*	*	*	72.0	18	18	*	81.2	47	55	*	81.5	*	*	*	70.3
5% Portland Type I	35	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-
	FC	78.7	2	2	2	75.6	1	1	0	85.3	3	3	3	85.6	2	2	2	73.8
5% Lime	35	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-
	FC	78.7	2	2	2	76.8	8	8	*	86.6	3	3	3	86.9	2	2	9	76.5
5% Calcilox A	35	-	*	*	*	-	*	82	*	-	*	*	*	-	*	*	*	-
	FC	78.7	19	19	13	75.6	8	4	4	85.3	3	10	7	85.6	2	2	6	73.8
5% Calcilox B	35	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-
10% Portland Type I	25	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-
	35	37.7	*	*	*	43.1	*	*	*	47.7	*	*	*	49.3	*	*	*	37.9
	FC	82.5	2	2	2	79.8	1	1	0	89.3	3	3	3	89.6	2	2	2	77.3
10% Lime	25	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-
	35	39.8	*	*	*	59.2	*	*	*	50.5	*	*	*	39.9	*	*	*	42.3
	FC	85.0	2	2	2	81.6	1	1	8	92.0	3	3	3	92.4	2	2	2	79.7
10% Calcilox A	25	-	+[3]	*	*	-	47	33	26	-	55	46	70	-	56	6.	57	-
	35	41.1	+	*	*	57.6	39	32	32	53.4	69	34	29	42.0	55	29	29	42.1
	FC	82.5	8	6	2	78.8	1	4	4	89.3	3	3	3	89.6	2	2	2	77.3
10% Calcilox B	35	-	+	+	+	-	39	18	32	-	49	29	29	-	63	39	55	-
15% Portland Type I	25	-	*	*	*	-	*	*	*	-	*	+	*	-	+	+	*	-
	35	-	*	*	+	-	*	+	*	-	+	+	+	-	*	*	*	-
15% Lime	25	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-
	35	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-
15% Calcilox A	25	-	+	+	+	-	26	19	33	-	36	24	24	-	49	29	30	-
	35	-	+	+	+	-	25	18	18	-	44	22	22	-	48	29	29	-
15% Calcilox B	35	-	+	85	63	-	39	32	25	-	44	22	22	-	39	29	29	-

Notes:

(1) The rate of stabilization was monitored by periodic testing with a Soiltest pocket penetrometer (Model CL-700). The penetrometer measures penetration resistance in tons per square foot (TSF) with a maximum attainable reading of 4.5 TSF.

(2) * Indicates that the specimen gained no strength at the end of the 90-day monitoring period.

(3) + Indicates that the specimen gained strength, but did not reach 4.5 TSF at the end of the 90-day monitoring period.

(4) Curing temperature measured in degrees Fahrenheit.

(5) Solids content after stabilization, dry weight percent.

TABLE XV

STABILIZATION RATE[1]
DAYS TO REACH 4.5 YSF

Sample Number																				
1106			Solids Content (%)	1107			Solids Content (%)	1110			Solids Content (%)	1111			Solids Content (%)	1112			Solids Content (%)	
39°	55°	72°		39°	55°	72°		39°	55°	72°		39°	55°	72°		39°	55°	72°		39°
*	*	*	61.7	*	*	*	49.7	*	*	*	53.9	*	*	*	61.4	*	*	*	41.6	*
*	*	*	61.4	*	*	*	52.0	*	*	*	55.0	*	*	*	62.2	*	*	*	42.3	*
47	55	*	81.5	*	*	*	70.3	62	41	*	73.7	76	56	*	81.0	28	35	*	70.5	82
*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-	*
3	3	3	85.6	2	2	2	73.8	2	2	2	77.4	3	3	6	85.0	2	2	2	74.0	5
*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-	*
3	3	3	86.9	2	2	9	76.5	41	31	*	78.6	23	23	*	86.4	2	2	2	75.2	41
*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-	*	83	*	-	*
3	10	7	85.6	2	2	6	73.8	20	16	12	77.4	8	8	6	85.0	2	2	2	74.0	28
*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-	90	90	*	-	*
*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-	*
*	*	*	49.3	*	*	*	37.9	*	*	*	38.6	*	*	*	54.1	*	*	*	37.6	*
3	3	3	89.6	2	2	2	77.3	2	2	2	81.1	3	3	6	89.1	2	2	2	77.6	5
*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-	*
*	*	*	39.9	*	*	*	42.3	*	*	*	42.6	*	*	*	61.8	*	*	*	43.5	*
3	3	3	92.4	2	2	2	79.7	31	16	*	83.5	23	23	*	91.8	2	2	2	79.9	41
55	46	70	-	56	64	57	-	*	*	69	-	*	*	*	-	*	90	55	-	*
69	34	29	42.0	55	29	29	42.1	*	*	*	43.4	83	75	89	61.3	*	*	*	38.6	*
3	3	3	89.6	2	2	2	77.3	9	9	6	81.1	8	8	6	89.1	2	2	2	77.6	5
49	29	29	-	63	39	55	-	*	*	*	-	*	75	75	-	41	28	28	-	*
*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-	*
*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-	*
*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-	*
*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-	*
36	24	24	-	49	29	30	-	*	*	*	-	90	90	*	-	90	69	76	-	*
44	22	22	-	48	29	29	-	90	82	*	-	75	55	54	-	90	90	69	-	70
44	22	22	-	39	29	29	-	75	36	55	-	55	41	48	-	28	28	21	-	62

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'ION RATE(1)
:ACH 4.5 YSF

Number																	
1110			Solids Content (%)	1111			Solids Content (%)	1112			Solids Content (%)	1113			Solids Content (%)	1114		
39°	55°	72°		39°	55°	72°		39°	55°	72°		39°	55°	72°		39°	55°	72°
*	*	*	53.9	*	*	*	61.4	*	*	*	41.6	*	*	*	43.4	*	*	*
*	*	*	55.0	*	*	*	62.2	*	*	*	42.3	*	*	*	47.4	*	*	*
62	41	*	73.7	76	56	*	81.0	28	35	*	79.5	82	82	*	71.6	90	62	*
*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*
2	2	2	77.4	3	3	6	85.0	2	2	2	74.0	5	5	5	75.2	2	2	2
*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*
41	31	*	78.6	23	23	*	86.4	2	2	2	75.2	41	41	*	76.4	28	21	*
*	*	*	-	*	*	*	-	*	83	*	-	*	*	*	-	*	*	*
20	16	12	77.4	8	8	6	85.0	2	2	2	74.0	28	15	15	75.2	10	10	10
*	*	*	-	*	*	*	-	90	90	*	-	*	*	*	-	*	*	*
*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*
*	*	*	38.6	*	*	*	54.1	*	*	*	37.6	*	*	*	37.7	*	*	*
2	2	2	81.1	3	3	6	89.1	2	2	2	77.6	5	5	5	78.8	2	2	2
*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*
*	*	*	42.6	*	*	*	61.8	*	*	*	43.5	*	*	*	41.9	*	*	*
31	16	*	83.5	23	23	*	91.8	2	2	2	79.9	41	28	*	81.1	10	21	*
*	*	69	-	*	*	*	-	*	90	55	-	*	*	*	-	*	*	*
*	*	*	43.4	83	75	89	61.3	*	*	*	38.6	*	*	*	39.1	*	*	*
9	9	6	81.1	8	8	6	89.1	2	2	2	77.6	5	5	5	78.8	2	7	2
*	*	*	-	*	75	75	-	41	28	28	-	*	*	*	-	*	*	*
*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*
*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*
*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*
*	*	*	-	90	90	*	-	90	69	76	-	*	*	*	-	65	65	90
90	82	*	-	75	55	54	-	90	90	69	-	70	62	70	-	84	77	90
75	36	55	-	55	41	48	-	28	28	21	-	62	48	41	-	56	56	35

3

Treatment																		
Additive	Mixed Solids (%)	Solids Content (%)(4)	1104 39°(3)	1104 55°	1104 72°	Solids Content (%)	1105 39°	1105 55°	1105 72°	Solids Content (%)	1106 39°	1106 55°	1106 72°	Solids Content (%)	1107 39°	1107 55°	1107 72°
Untreated	25	52.1	*(2)	*	*	55.4	*	*	*	56.5	*	*	*	61.7	*	*	*
	35	55.9	*	*	*	59.8	60	*	*	59.5	*	*	*	61.4	*	*	*
	FC	75.0	*	*	*	72.0	3	8	*	81.2	13	9	*	81.5	22	22	*
5% Portland Type I	35	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*
	FC	78.7	1	1	1	75.6	1	1	1	85.3	1	1	1	85.6	1	1	1
5% Lime	35	-	*	*	*	-	88	*	*	-	*	*	*	-	*	*	*
	FC	78.7	1	1	1	76.8	1	1	1	86.6	1	1	1	86.9	1	1	1
5% CalciloxA	35	-	*	*	*	-	50	38	35	-	48	30	21	-	*	61	54
	FC	78.7	10	11	4	75.6	1	1	1	85.3	1	1	1	85.6	1	1	1
5% CalciloxB	35	-	*	*	*	-	53	37	50	-	88	55	47	-	*	55	48
10% Portland Type I	25	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*
	35	37.7	*	*	*	43.1	*	*	*	47.7	*	*	*	49.3	*	*	*
	FC	82.5	1	1	1	79.8	1	1	1	89.3	1	1	1	89.6	1	1	1
10% Lime	25	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*
	35	39.8	*	*	*	59.2	*	*	*	50.5	*	*	*	39.9	*	*	*
	FC	85.0	1	1	1	81.6	1	1	1	92.0	1	1	1	92.4	1	1	1
10% CalciloxA	25	-	*	*	*	-	19	11	8	-	27	16	17	-	32	26	15
	35	41.1	*	*	70	57.6	18	12	10	53.4	34	14	11	42.0	34	17	10
	FC	82.5	2	2	1	78.8	1	1	1	89.3	1	1	1	89.6	1	1	1
10% CalciloxB	35	-	*	61	*	-	22	14	12	-	26	13	11	-	33	21	17
15% Portaind Type I	25	-	*	*	*	-	*	*	*	-	*	*	*	-	91	87	*
	35	-	*	*	*	-	*	*	*	-	*	*	66	-	*	*	*
15% Lime	25	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*
	35	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*
15% CalciloxA	25	-	58	41	34	-	17	8	13	-	18	11	8	-	24	9	9
	35	-	74	33	18	-	16	8	6	-	18	12	9	-	22	16	11
15% CalciloxB	35	-	49	21	17	-	21	12	10	-	21	11	10	-	16	12	7

Notes:

(1) The rate of stabilization was monitored by periodic testing with a Soiltest pocket penetrometer (Model CL-700)

The penetrometer measures in tons per square foot (TSF) with a maximum attainable reading of 4.5 TSF.

(2) *Indicates that the specimen did not reach 2.0 TSF at the end of the 90-day monitoring period.

(3) Curing temperature measured in degrees Fahrenheit.

(4) Solids content after stabilization, dry weight percent.

TABLE XVI

STABILIZATION RATE [1]
DAYS TO REACH 2.0 TSF

Solids Content (%)	1106			Solids Content (%)	1107			Solids Content (%)	1110			Solids Content (%)	1111			Solids Content (%)		
	39°	55°	72°		39°	55°	72°		39°	55°	72°		39°	55°	72°		39°	
6.5	*	*	*	61.7	*	*	*	49.7	*	*	*	53.5	*	*	*	61.4	*	
9.5	*	*	*	61.4	*	*	*	52.0	*	*	*	55.0	*	*	*	62.2	*	
1.2	13	9	*	81.5	22	22	*	70.3	42	17	*	73.7	43	42	1	81.9	1	
-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-	*	
5.3	1	1	1	85.6	1	1	1	73.8	1	1	1	77.4	1	1	2	85.0	1	
-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-	*	
6.6	1	1	1	86.9	1	1	1	76.5	14	6	*	78.5	5	5	18	86.4	1	
-	48	30	21	-	*	61	54	-	*	*	*	-	*	*	*	-	45	
5.3	1	1	1	85.6	1	1	1	73.8	7	5	4	77.4	1	1	2	85.0	1	
-	88	55	47	-	*	55	48	-	*	*	*	-	*	*	83	-	48	
-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-	*	
7.7	*	*	*	49.3	*	*	*	37.9	*	*	*	38.6	*	*	*	54.1	*	
9.3	1	1	1	89.6	1	1	1	77.3	1	1	1	81.1	1	1	2	89.1	1	
-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-	*	
0.5	*	*	*	39.9	*	*	*	42.3	*	*	*	42.6	*	*	*	61.8	*	
2.0	1	1	1	92.4	1	1	1	79.7	2	3	3	83.5	2	3	5	91.8	1	
-	27	16	17	-	32	26	15	-	*	*	63	-	71	48	53	-	26	3
3.4	34	14	11	42.0	34	17	10	42.1	75	49	57	43.4	48	27	22	61.3	63	6
9.3	1	1	1	89.6	1	1	1	77.3	4	3	3	81.1	1	1	2	89.1	1	
-	26	13	11	-	33	21	17	-	62	25	32	-	53	36	19	-	21	1
-	*	*	*	-	91	87	*	-	*	*	*	-	*	*	*	-	*	
-	*	*	66	-	*	*	*	-	*	*	*	-	*	*	*	-	*	
-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-	*	
-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-	*	
-	18	13	8	-	24	9	9	-	46	44	40	-	37	28	22	-	32	1
-	18	12	9	-	22	16	11	-	41	24	22	-	34	30	14	-	34	3
-	21	11	10	-	16	12	7	-	34	18	12	-	31	25	11	-	19	1

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TABLE XVI

STABILIZATION RATE[1]
DAYS TO REACH 2.0 TSF

Sample Number																			
	Solids Content (%)	1110			Solids Content (%)	1111			Solids Content (%)	1112			Solids Content (%)	1113			Solids Content (%)	1114		
		39°	55°	72°		39°	55°	72°		39°	55°	72°		39°	55°	72°		39°	55°	72°
	49.7	*	*	*	53.9	*	*	*	61.4	*	*	*	41.6	*	*	*	43.4	*	*	*
	52.0	*	*	*	55.0	*	*	*	62.2	*	*	*	42.3	*	*	*	47.4	*	*	*
	70.3	42	17	*	73.7	43	42	-	81.0	1	1	*	70.5	59	56	*	71.6	68	42	*
	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*
	73.8	1	1	1	77.4	1	1	2	85.0	1	1	1	74.0	2	2	2	75.2	1	1	1
	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*
	76.5	14	6	*	78.6	5	5	18	86.4	1	1	1	75.2	28	20	*	76.4	5	4	23
	-	*	*	*	-	*	*	*	-	45	34	55	-	*	*	*	-	*	*	*
	73.8	7	5	4	77.4	1	1	2	85.0	1	1	1	74.0	15	7	4	75.2	3	3	1
	-	*	*	*	-	*	*	83	-	48	39	27	-	*	*	*	-	*	*	*
	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*
	37.9	*	*	*	38.6	*	*	*	54.1	*	*	*	37.6	*	*	*	37.7	*	*	*
	77.3	1	1	1	81.1	1	1	2	89.1	1	1	1	77.6	2	2	2	78.8	2	1	1
	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*
	42.3	*	*	*	42.6	*	*	*	61.8	*	*	*	43.5	*	*	*	41.9	*	*	*
	79.7	2	3	9	83.5	2	3	5	91.8	1	1	1	79.9	15	11	68	81.1	6	5	19
	-	*	*	63	-	71	48	53	-	26	39	19	-	*	*	*	-	65	52	68
	42.1	75	48	57	43.4	48	27	22	61.3	63	69	44	38.6	62	57	39	39.1	60	49	59
	77.3	4	3	3	81.1	1	1	2	89.1	1	1	1	77.6	2	2	2	78.8	2	1	1
	-	62	25	32	-	53	36	19	-	21	15	12	-	67	59	40	-	61	26	21
	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*
	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*
	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*
	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*	-	*	*	*
	-	46	44	40	-	37	28	22	-	32	19	21	-	46	48	43	-	29	22	32
	-	41	24	22	-	34	30	14	-	34	34	19	-	25	21	12	-	32	20	14
	-	34	18	12	-	31	23	11	-	19	15	11	-	25	21	13	-	28	16	11

TABLE XVII-A

DRAVO CORPORATION
NEW TECHNOLOGY DEPARTMENT

REF.NO. 5872 (Activity Code) 108-4 (Proj.No.) ( ) (Lab. No.)

PARTICLE SIZE ANALYSIS

Sample Description: All Samples

Date: 12-5-77
Test No.: 10
Tested by: R.P.

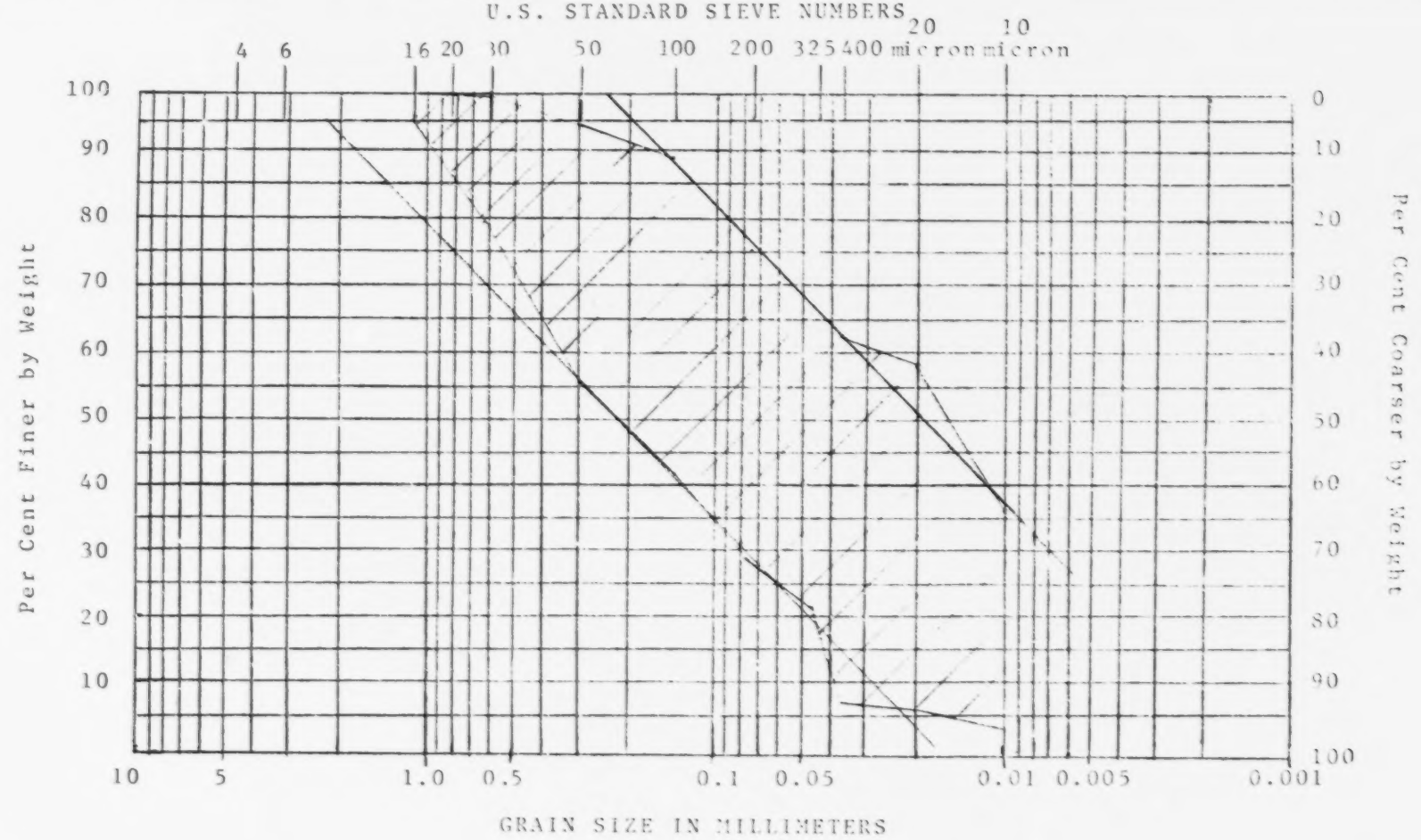
U.S. STANDARD SIEVE NUMBERS
4 6 16 20 30 50 100 200 325 400 20 micron 10 micron
Per Cent Finer by Weight
100 90 80 70 60 50 40 30 20 10
0 10 20 30 40 50 60 70 80 90 100
Per Cent Coarser by Weight
10 5 1.0 0.5 0.1 0.05 0.01 0.005 0.001
GRAIN SIZE IN MILLIMETERS

TABLE XVII-B

RANK - GROUPING OF SAMPLES FROM TEST RESULTS

TESTS

Sample	Particle Size(1)	Specific Gravity	Liquid Limit	Optimum Water Content	Settling	Consolidation C_c	Direct Shear Cohesion	Permeability	Filtration
1113	3	3	2	3	1	1	6*	3	2
1104	2	1	5*	6*	6*	2	1	5*	3
1110	1	6*	3	1	2	5*	5*	2	6*
1111	4	5	4	4	4	4	3*	4	5
1114	5	2*	1*	5	5	3*	4	6	9*
1107	8*	4	7*	9*	9*	8*	2*	1*	1*
1105	6*	8	6*	2*	7	7	8	8	8
1106	7	7	9	8	8	9	7	7	4*
1112	9	9	8	7	3*	6*	9	9	7

*Test Results that Did Not Conform to Ranking

(1) Ranked Fine to Coarse

PARTICLE SIZE ANALYSIS

The grain size analysis is determined by both a wet and dry sieve segregation.

Approximately 200 grams of the settled solids are washed through a vibrating stack of sieves consisting of 200, 325, and 400 mesh sieves. All of the wash water and its accompanying solids are retained. The wash water is filtered and the solids retained by the filter and sieves are oven-dried and weighed.

The dried solids retained on the 200 mesh sieve are placed in a stack of sieves containing 16, 30, 50, 100, 200, and 325 mesh sieves and placed on the Ro-Tap for a period of approximately 10 minutes.

The solids retained by each sieve are weighed, and the percent solids retained by each sieve determined by:

$$\text{Percent solids retained} = \frac{\text{Weight of solids retained}}{\text{Total Weight of Solids}} \times 100\%.$$

To obtain the 20 and 10 micron particle size fraction, 1 gram and 0.5 gram, respectively, of minus 400 mesh solids are used for the determination.

The sieve with the sample is placed in a dish with dispersing liquid and agitated with a pumping action causing the liquid to wash up and back through the sieve. The dispersing liquid is changed as it becomes contaminated, and the agitation of the sieve continued until the dispersing liquid remains clear.

The retained solids are then washed with methanol and dried.

The percent solids retained is calculated as before.

SETTLING TESTS

The settling test determines the rate at which the slurry solids will settle and the concentration to which they will settle.

To perform the test, a known weight of solids is placed in a 1000 milliliter graduate and the volume adjusted to the 1000 milliliter mark by the addition of water. The contents of the graduate are thoroughly mixed and the graduate placed in a location where it will be undisturbed. Immediately after mixing, a timer is started; and the settled volume of the slurry portion is recorded with respect to the time to settle. Settled volume and time readings are taken periodically up to 7 days.

A graph, plotting the change in settled solids height against the time for settling, shows the settling characteristics of the solids. From the height of the settled slurry and the weight of the solids, the settled percent solids is calculated and then verified by an oven-dried sample.

LEAF FILTER TESTS

The cycle time of a leaf filter test is analogous to the filter drum speed. Generally the faster the drum speed the higher the output, but the cake may be thinner and sometimes wetter. The filter leaf test determines the selection of the drum speed which is usually a compromise of these conditions.

The filter cycle of a drum filter is the total time required for one revolution of the drum which is four times the form time (cake forming) or two times the dry time. The form time is dependent on the slurry's ability to produce a dischargeable cake in a reasonably short time.

The leaf filter consists of a circular area of 1/10 square foot over which a filter cloth can be mounted, and a vacuum outlet situated so that, when a vacuum is applied, the solids in the slurry will be collected on the filter cloth.

In operation, the filter leaf is submerged in a constantly stirred slurry. The vacuum is turned on for the required form time, then the filter leaf is removed from the slurry for the required dry time and the vacuum turned off. The readings of vacuum, times, air flow during drying and other pertinent information that relate to the drum filter operation are taken during the immersion and dry times. The filtrate is collected and measured along with the weight and the thickness of the cake on the filter leaf. The cake is then dried and reweighed.

From the date, the percent cake moisture, dry pounds per square foot of filter cloth per hour, and gallons of filtrate per square foot per hour are calculated for the set of operating conditions.

The test is repeated with changes in the operating variables until the most economical filtration rate is obtained. The set of operating conditions that produce this filtration rate are then applied to the drum filter operation.

ATTERBERG LIMITS AND INDICES

The Atterberg consistency limits of a particulate solid passing a No. 40 sieve provide indications of the surface chemical characteristics of the material such as plasticity or friability, shrinkage and swell, and bonding power. The Atterberg limits are the liquid limit, plastic limit, and plasticity index.

The moisture content above which the material becomes liquid upon stirring is called the liquid limit. The minimum moisture content at which the material acts as a plastic solid is called the plastic limit. The numerical difference between the liquid limit and the plastic limit is the plasticity index.

To determine the liquid limit of a material, a portion passing a No. 40 sieve is mixed with water to a paste consistency. It is then placed in a spherical shaped brass cup and the surface smoothed to provide a pat with a maximum thickness of one centimeter. The pat is divided into two segments with a grooving tool of standard shape and dimensions. The brass cup is mounted in such a way that by turning a crank, it can be raised and allowed to fall sharply onto a hard-rubber base. The shock produced by the fall causes the adjacent sides of the divided pat to flow together. The wetter the pat, the fewer shocks will be required to close the groove; the drier the pat, the greater the number of blows. The moisture content at which 25 blows causes the groove to close is defined as the liquid limit of the material.

To determine the plastic limit of the material, a small quantity of the material is rolled out with the palm of the hand on a flat surface until a thread is formed. When the thread is rolled to a diameter of 1/8 inch and becomes brittle so that it will no longer hold together in a continuous thread, the moisture content is determined and defines the plastic limit.

SPECIFIC GRAVITY TEST

The specific gravity of a particulate solid is the ratio of the weight of a given volume of solid particles to the weight of an equal volume of water at a temperature of $4^{o}C$.

To perform a specific gravity test, a volumetric flask is filled to the volume mark with the particulate solid and water, weighed to the nearest 0.1 g. (W_1) and the temperature determined ($_T$).

The contents of the flask are removed, and the dry weight of the solids (W_s) is determined to the nearest 0.1 g.

The flask is refilled with water to the volumetric mark after adjusting the temperature to that of the slurry, and weighed to the nearest 0.1 gram (W_2).

The specific gravity can be calculated from the formula: $Gs = \frac{W_s G_T}{W_s - W_1 + W_2}$

where G_T = specific gravity of water at temperature T

W_s = dry weight of the solids

W_1 = weight of flask, solids and water

W_2 = weight of flask and water.

COMPACTION

Compacting a particulate solids-water mixture is desirable for: 1) Decreasing future settlement, 2) Increasing the shear strength, and 3) Decreasing the permeability. The compaction test is a means of determining the optimum water content of a compacted mixture that maximizes these qualities.

The standard Proctor compaction test utilizes a 4 inch diameter by 4.6 inch high cylindrical mold with a capacity of 1/30 cubic foot. The material is compacted into the mold in three layers with 25 blows per layer from a 5.5 pound hammer free-falling a distance of one foot, producing a compactive energy of 12,400 foot pounds per cubic foot of material.

The compacted material is weighed, and a representative sample is removed for a solids and water content determination.

A series of tests are run on the same material with varying water contents.

A plot of the solids dry density mold versus the water content determines a curve that, with an increase in the water content, shows a density increase. As more water is added to the dry solids, the solids level in the constant volume mold decreases. The water content at the maximum dry density is the optimum water content.

PERMEABILITY

Permeability is a property which indicates the ease with which water will flow through the spaces between particulate solids in a mass.

In the laboratory method of determining the permeability of a particulate solid by the constant head method, a specimen of length "L" and cross-sectional area "A", is placed in a tight-fitting tube. A standpipe from an elevated constant level reservoir introduces water to the top of the specimen, and the volume of water passing through the specimen is measured with respect to time.

The flow of water "q" is directly proportional to the area "A" and to the ratio of the height of the water column "H", and inversely proportional to the length of the specimen "L". This relationship can be expressed by the equation $q = \frac{HA}{L}$ where "k" is the constant of proportionality called the coefficient of permeability, or permeability with units of velocity.

The permeability, then, is a measure of the velocity of the water as it flows through the specimen, expressed in centimeters per second.

A permeability of 10^{-4} centimeters per second is frequently used as a determination between pervious and impervious materials.

DIRECT SHEAR TEST

A direct shear test provides a means of determining the values of the friction angle and the cohesion of a particulate solid.

In the direct shear test, a sample in the form of a low cylinder is placed in a shear mold that permits the upper portion of the mass to slide in relation to the lower portion. The plane through the sample on which the sliding motion is produced is the shear plane.

A known load is applied in the direction normal to the shear plane and the shearing load applied to the upper portion of the specimen. Most tests are strain controlled, that is, the upper portion of the shear mold is driven at a constant rate, and the shearing resistance is monitored. Generally, the shearing force gradually increases to a constant ultimate value.

When testing a material in direct shear, a minimum of three separate tests are performed with a different normal load for each test. To provide consistency in the test specimens, each specimen is consolidated under a normal load, constant for all specimens, that is greater than the testing loads.

The normal load and the maximum applied shearing force are divided by the cross-sectional area of the specimen at the shear plane to give the unit normal pressure and the shear stress at failure. These values for each test are plotted on a graph and generally the points will approximate a straight line. The angle this line makes with the horizontal constitutes the friction angle of the material, and the intersection at zero normal stress is the cohesive stress.

CONSOLIDATION TEST

The purpose of a consolidation test is to obtain data used to predict the rate and the amount of settlement of a particulate solid when subjected to a load. The load may be the result of a structure or overburden.

To perform this test, a specimen is encased in a ring to prevent lateral movement and sandwiched between two porous plates. The specimen is submerged in water, and vertical pressure or stress is applied to the plates to compress the specimen. It is allowed to remain until the compression virtually ceases, and then a much larger stress is added. This is repeated for the range of stresses to which the material is likely to be subjected. The amount of compression of the material is measured with a micrometer dial.

Generally, the initial loading on the material is 1/2 kilogram per square centimeter and progresses to 8 kilograms per square centimeter, with each loading two times the preceding load. When 90% consolidation has been reached at a particular loading, the load is changed.

After the consolidation is completed, the specimen is removed, and its dry weight and dry density determined. The initial void ratio and the void ratio at equilibrium at each load increment can be computed from the volume of the solids and the volume of the specimen.

The compression strain is the result of a decrease in the volume of the voids; therefore, it is convenient to express the stress-strain relationship in terms of void ratio and unit pressure.

A plot of the equilibrium void ratio versus the log of the applied pressure establishes a curve whose slope is numerically equal to the compression index (C_c), which is a measure of the compressibility of the material.

The percent compression for each load can be determined by the change in the vertical dial reading for each load increment.

The rate of consolidation is determined from the vertical dial readings versus time for each load and is related to the permeability of the material which controls the rate of flow of the escaping water.

The rate of consolidation under a load increment is represented by the coefficient of consolidation, C_v. At a particular load increment $C_v = \frac{.0848\ H^2}{t_{90}}$ where

H = average thickness per drainage surface

t_{90} = time for 90% compression.

The time - rate of settlement of a particular load for 90% consolidation can be determined by

$$t = \frac{.848\ H^2}{C_v}$$

t = time for settlement

H = maximum distance the pore water must flow to escape

C_v = coefficient of consolidation at the particular load.

UNCONFINED COMPRESSION TEST

The unconfined compression test is used to measure the compressive strength of a cylinder of material to which no lateral support is offered. Based upon a combination of theoretical and empirical considerations, the ratio of compressive strength to shear strength is equal to two. Therefore, the test is also a simple and quick laboratory method of measuring the shear strength of the material.

The unconfined compression test imposes uniform stresses and strains on the specimen and causes the failure surface to develop in the weakest portion of the specimen.

The uniformity of the prepared test specimen is very important for consistent results; thus, a stabilized specimen is allowed to stabilize in a specimen mold. The specimen is made cylindrical with a length to diameter ratio of approximately two.

The ends of the specimen are trimmed to a plane normal to the longitudinal axis, and the specimen is placed in the testing machine. A force is applied to the longitudinal axis of the specimen until a failure or a strain of 20% is reached. The strain is determined by a dial gauge that measures the decrease in the length of the specimen as the force is applied.

The amount of strain at failure is used to calculate the average cross-sectional area of the specimen at failure. The maximum force required to fail the specimen divided by the average cross-sectional area at failure gives the maximum compressive stress of the specimen. One-half of the compressive stress is equal to the shear stress.

RATE OF STABILIZATION

Stabilization consists of changing a water-particulate solids mixture from a slurry or soft mass to a hardened material exhibiting engineering properties. This change is usually accomplished by the addition of stabilizers that react with the particulate solids, or with themselves, to produce the hardened condition.

The rate of stabilization is the degree of stabilization throughout the time span in which the stabilization takes place.

Stabilization specimens are prepared by adjusting the percent solids of a water-particulate slurry to a definite value and mixing with a stabilizer, which is added on a weight percent of the slurry solids. The slurry-stabilizer mixture is then stored at a constant temperature and allowed to stabilize.

The rate of stabilization is determined by periodically measuring the hardness of the specimen during the stabilizing period.

The hardness measurements are determined with a Soiltest Pocket Penetrometer Model CL-700. This instrument consists of a flat-ended one-quarter inch diameter (0.05 square inches) spring-loaded rod with a circular mark, serving as a depth gauge, one-quarter inch from the end. In practice, the rod is inserted into the material to the depth of the circular mark, and the amount of spring compression is measured on a scale calibrated in tons per square foot.

The penetrometer reading, measuring the resistance to penetration in tons per square foot, at periodic time intervals is used to determine a qualitative relationship between the hardening time and penetration resistance (degree of stabilization) of the mixture.